Superconducting Detectors for Superlight Dark Matter

Yonit Hochberg

YH, Zhao and Zurek, PRL 116 no.1, 011301 (2015)
YH, Pyle, Zhao and Zurek, JHEP 1608, 057 (2016)
YH, Lin and Zurek, PRD 94 no.1, 015019 (2016)

THE HEBREW UNIVERSITY OF JERUSALEM

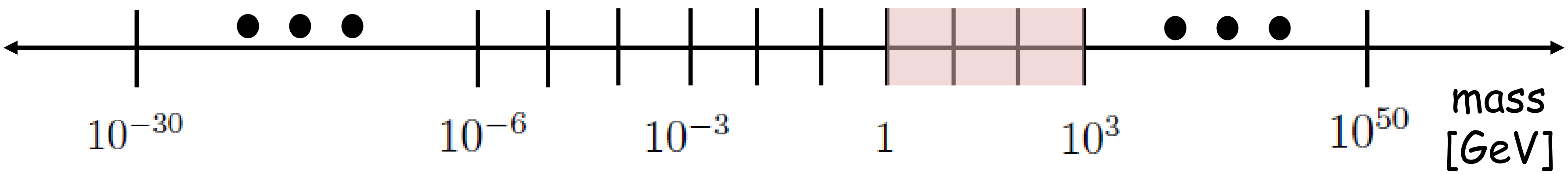
Outline

- What?
- How?
- Rates
- Results

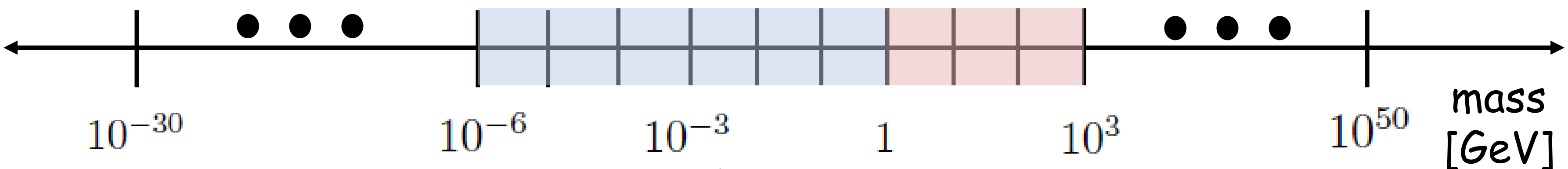
What?

“Beyond the WIMP lalalalalalala”

Beyond the WIMP

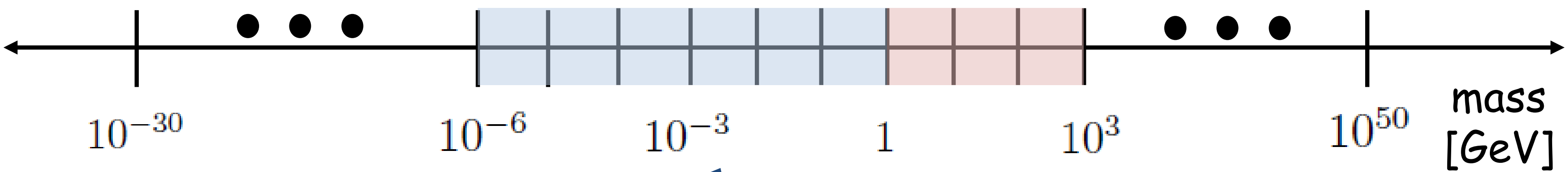


Beyond the WIMP



Go lighter!
keV-GeV

Beyond the WIMP



Theory:

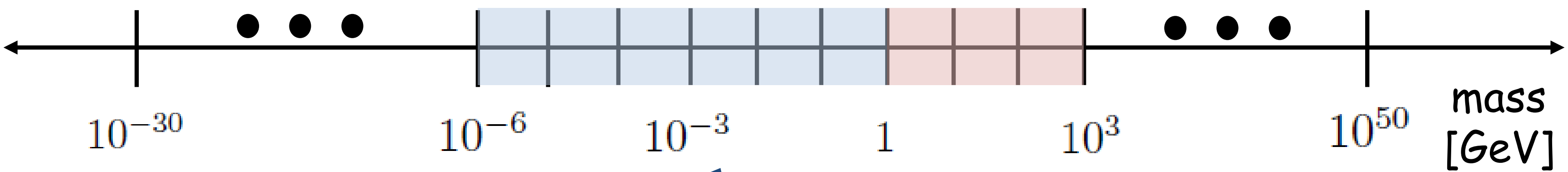
Lots of activity in recent years

e.g.: Asymmetric dark matter [Kaplan, Luty, Zurek, 2009]

SIMPs [**YH**, Kuflik, Volansky, Wacker, 2014]

Forbidden dark matter [Griest, Seckel, 1991; D'Agnolo, Ruderman, 2015]

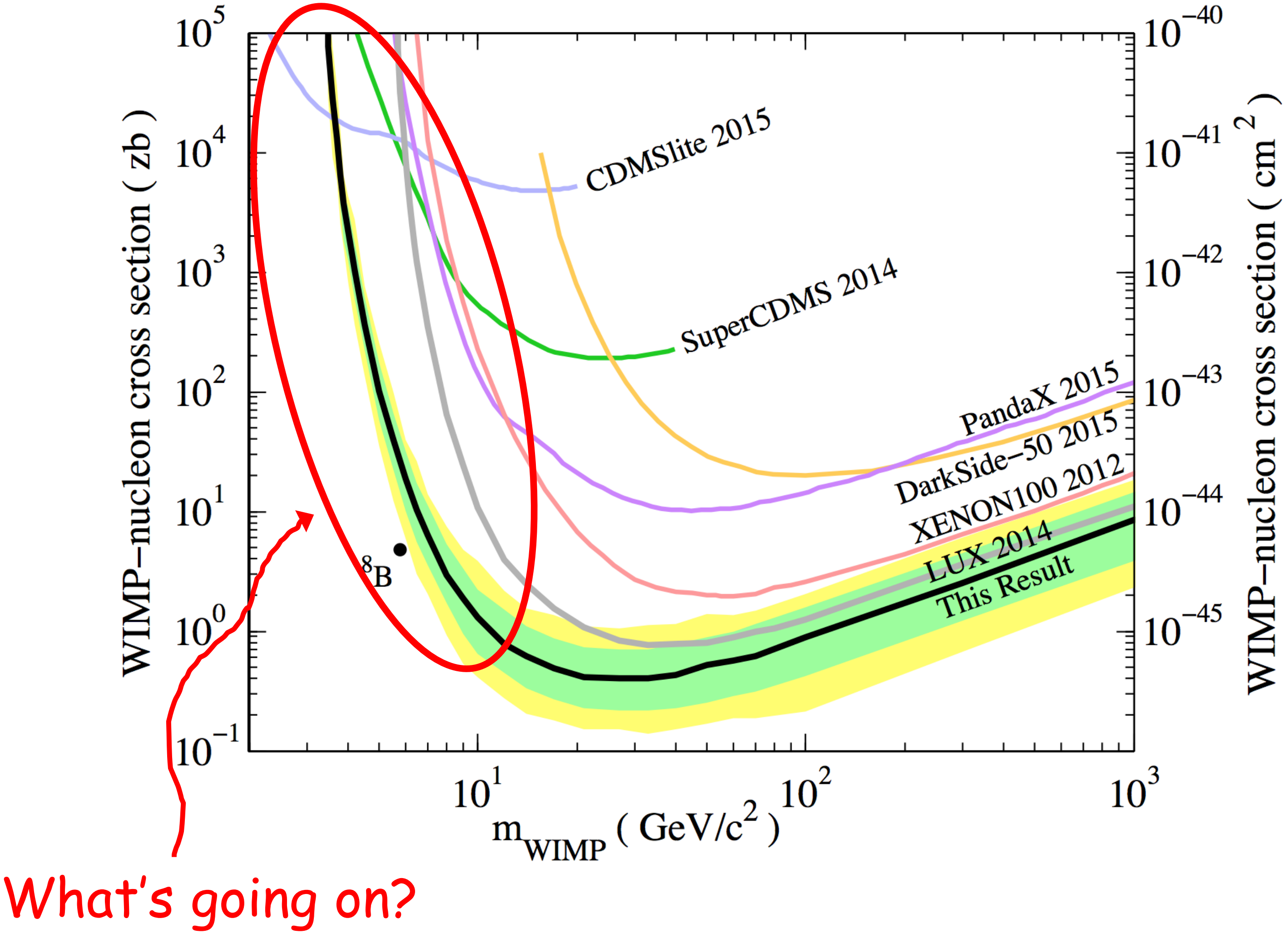
Beyond the WIMP



<u>Experiment:</u>
direct detection
of keV-GeV
dark matter
via superconductors

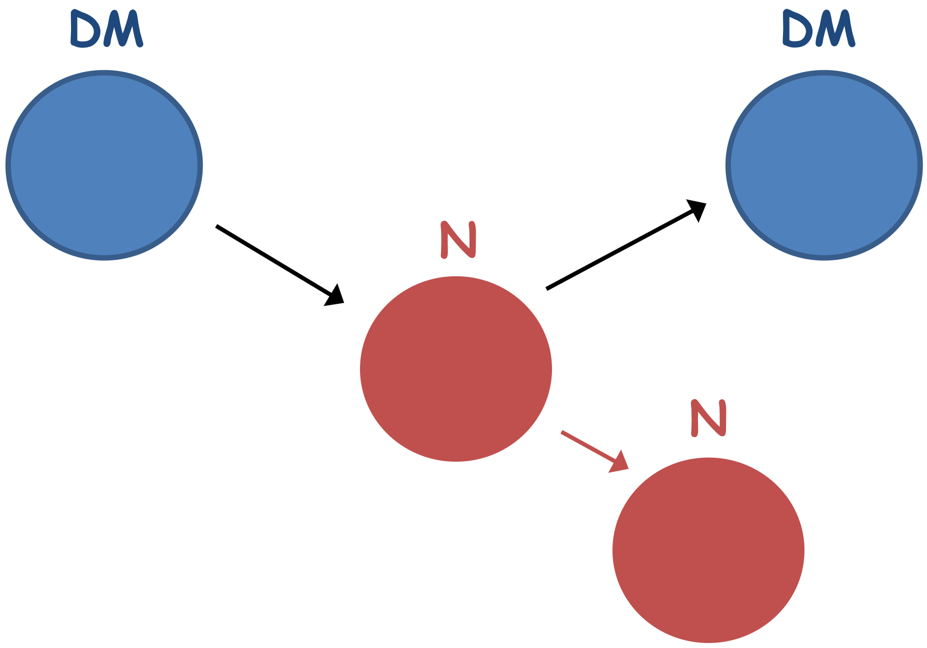
How?

Direct Detection



Direct Detection

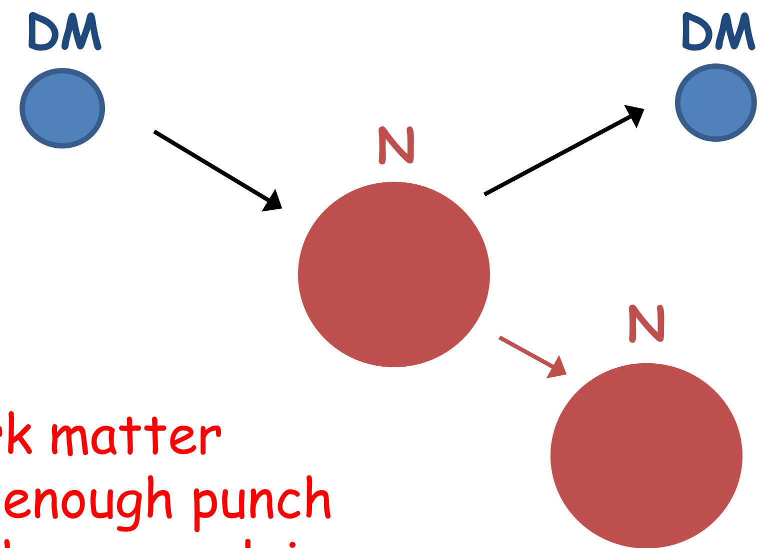
- Looking at nuclear recoils: think billiard balls



$$E_{\rm NR} = \frac{q^2}{2m_N} = \frac{(m_{\rm DM} v)^2}{2m_N} \gtrsim E_{\rm th} \sim {\rm keV}$$

Direct Detection

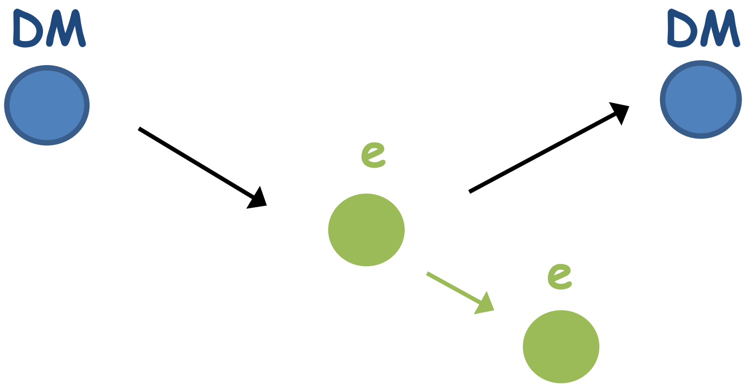
- Looking at nuclear recoils: think billiard balls



light dark matter
doesn't have enough punch
to kick the heavy nuclei

Direct Detection

- Light dark matter: scatter off electrons!

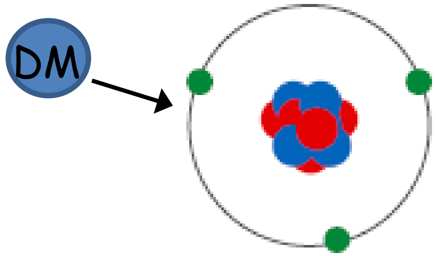


Direct Detection

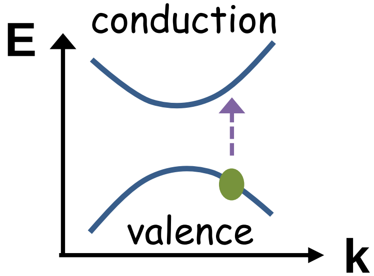
- Light dark matter: scatter off electrons!

Kinetic energy available: $E_D \sim \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 \sim 10^{-6} m_{\rm DM}$

$m_{\rm DM} \sim \text{MeV} \Rightarrow E_D \sim \text{eV}$ ⟹ electron ionization, semiconductors



Xenon: ~12 eV



Ge, Si: ~eV

[Essig et al 2012;
Graham et al 2012;
Xenon10 data:
Essig et al 2012]

Direct Detection

- Light dark matter: scatter off electrons!

Kinetic energy available: $E_D \sim \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 \sim 10^{-6} m_{\rm DM}$

$m_{\rm DM} \sim \text{MeV} \Rightarrow E_D \sim \text{eV}$ $\Rightarrow$ electron ionization, semiconductors

$m_{\rm DM} \sim \text{keV} \Rightarrow E_D \sim \text{mili-eV}$ $\Rightarrow$?

Direct Detection

- Light dark matter: scatter off electrons!

Kinetic energy available: $E_D \sim \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 \sim 10^{-6} m_{\rm DM}$

$m_{\rm DM} \sim \mathrm{MeV} \Rightarrow E_D \sim \mathrm{eV}$ ⟹ electron ionization, semiconductors

$m_{\rm DM} \sim \mathrm{keV} \Rightarrow E_D \sim \text{mili-eV}$ ⟹ **Superconductors!**

[**YH**, Zhao and Zurek, PRL 2015;
YH, Pyle, Zhao and Zurek, JHEP 2016]

Kinematics

Target at rest: $E_D \sim \frac{q^2}{2m_T}$

- Target = N: $q_{\max} \sim 2\mu_r v_{\rm DM} \sim 2m_{\rm DM} v_{\rm DM}$

  Even for $\sigma_E \sim {\rm eV}$, only $m_{\rm DM} \sim \mathcal{O}(100'{\rm s\ MeV})$ detectable

- Target = e: $m_{\rm DM} \sim {\rm keV} \Rightarrow E_D \sim 10^{-6}\ {\rm eV}$

  $m_{\rm DM} \sim {\rm MeV} \Rightarrow E_D \sim {\rm eV}$ [seminconductors]

  Even $\sigma_E \sim {\rm meV}$ won't allow sensitivity to keV DM

Kinematics

Target w/ velocity: $$E_D \sim \left(\frac{\vec{q}^2}{2m_T} + \vec{q}\cdot\vec{v}_T\right) + \delta$$

- $\underline{m_{\rm DM} \gg m_T\text{:}}$ DM barely affected

  $$v_T \rightarrow v_T + 2v_{\rm DM}$$

  $$E_D^{\rm max} = \frac{1}{2}m_T\left[(v_T + 2v_{\rm DM})^2 - v_T^2\right]$$

- $\underline{m_{\rm DM} \ll m_T\text{:}}$ Target can fully stop the DM

  $$E_D^{\rm max} \sim \frac{1}{2}m_{\rm DM}v_{\rm DM}^2$$

  $\sigma_E \sim \mathrm{meV}$ for $m_{\rm DM} \sim \mathrm{keV}$!

Kinematics

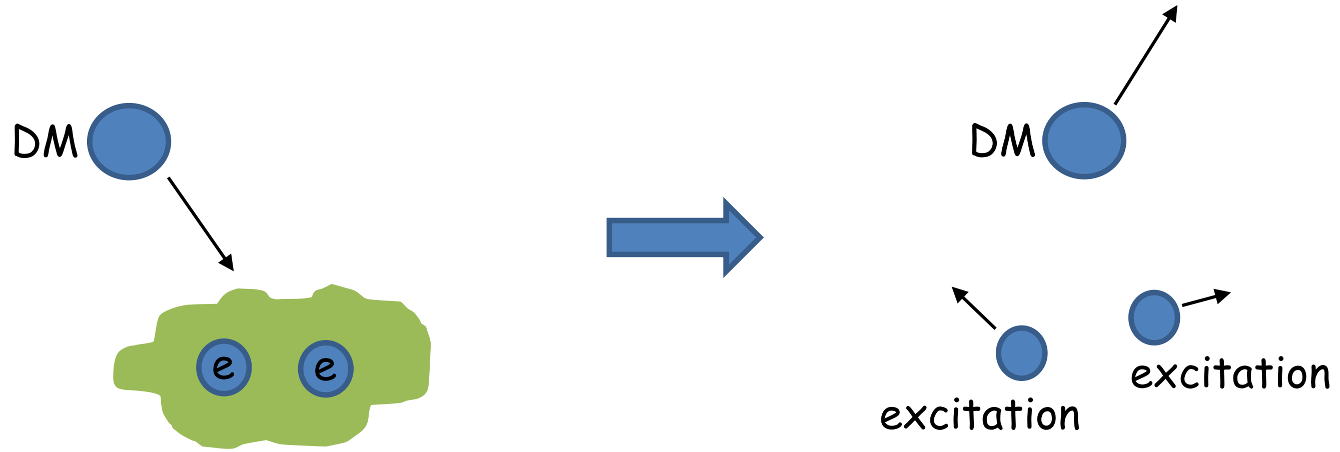
Target w/ velocity: $E_D \sim \left(\frac{\vec{q}^2}{2m_T} + \vec{q}\cdot\vec{v}_T\right) + \delta$

Fermi-degenerate materials
have velocity!

Focus on superconductor targets.

Superconductor Cheat Sheet

- Ground state of superconductor = Cooper pairs;
  Binding energy (gap) $\Delta \lesssim$ mili-eV
- <u>The idea:</u>
  DM scatters with Cooper pairs, deposits enough energy, breaks Cooper pairs, creating excitations → detect

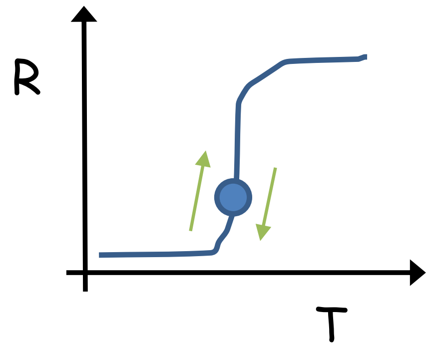


Superconductor Cheat Sheet

- For energies exceeding the gap, scatter with free electrons in a Fermi-degenerate sea ("coherence factor" → 1)

- Ram an electron, create excitations which random walk until collected by e.g. a Transition Edge Sensor (TES)

Heat calorimeter



TESs used to
detect microwaves and x-rays
in astro applications
(e.g. ACT, SPT, SuperCDMS)

Superconductor Cheat Sheet

- Current status? Not there yet

TES	T_c [mK]	Volume [μm $\times$ μm $\times$ nm]	Power Noise [W/$\sqrt{\text{Hz}}$]	σ_E^{now} [meV]	σ_E^{scale} [meV]
W [3]	125	$25 \times 25 \times 35$	2.72×10^{-18}	120	1.1
Ti [5]	50	$6 \times 0.4 \times 56$	2.97×10^{-20}	47	22
MoCu [6]	110.6	$100 \times 100 \times 200$	4.2×10^{-19}	295.4	0.3

- Need to beat noise
- Energy resolution $\sigma_E \propto \sqrt{T^3 V}$ $\Rightarrow$ Reduce temperature and volume for O(meV) resolution

(See talk by Matt Pyle tomorrow)

Superconductor Cheat Sheet

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- Need to beat noise
- Energy resolution $\sigma_E \propto \sqrt{T^3 V}$ $\Rightarrow$ Reduce temperature and volume for O(meV) resolution

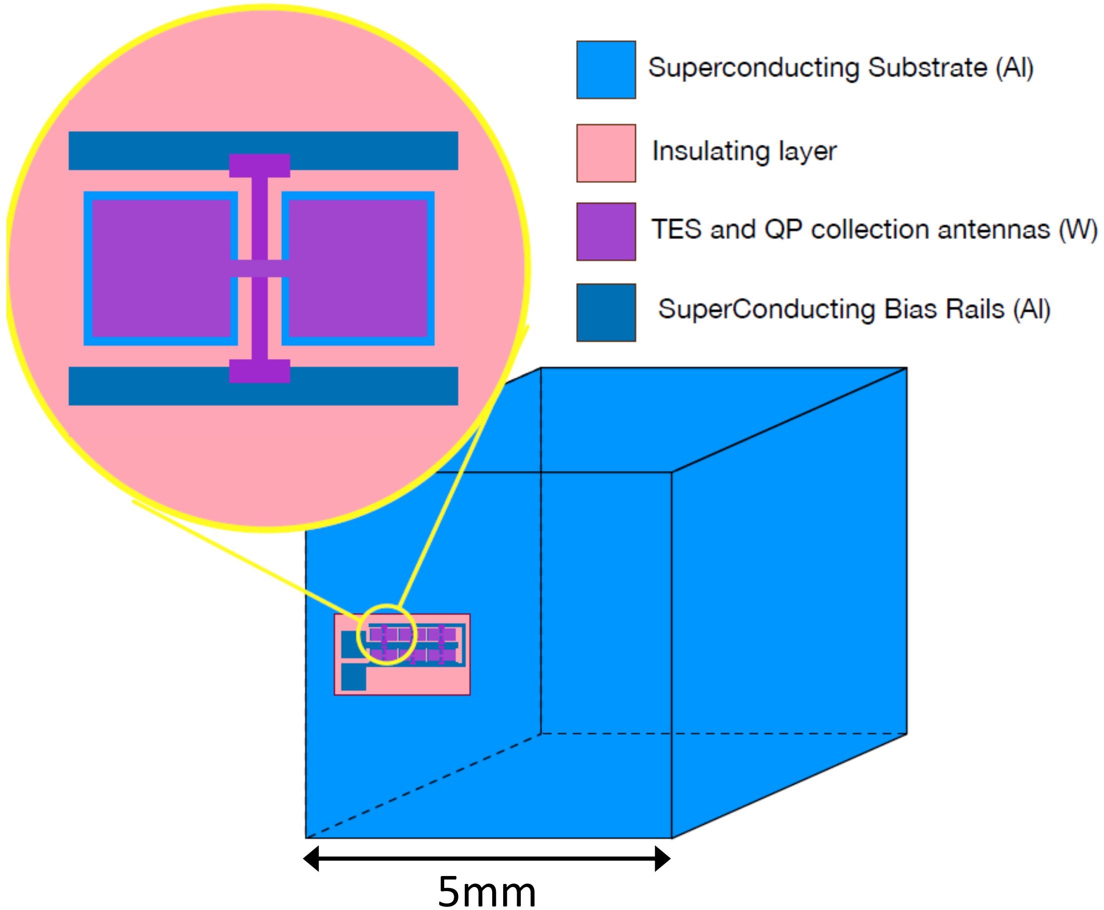
(Volume: $25\mu\text{m} \times 6\mu\text{m} \times 35\text{nm}$, Operating temp': $T_c \sim 10\text{mK}$)

Detector Concept

<u>Basic device idea:</u>
Large exposure but high energy resolution = excitation concentration

(E.g. SuperCDMS)

Absorber →
Collection fins→
TES

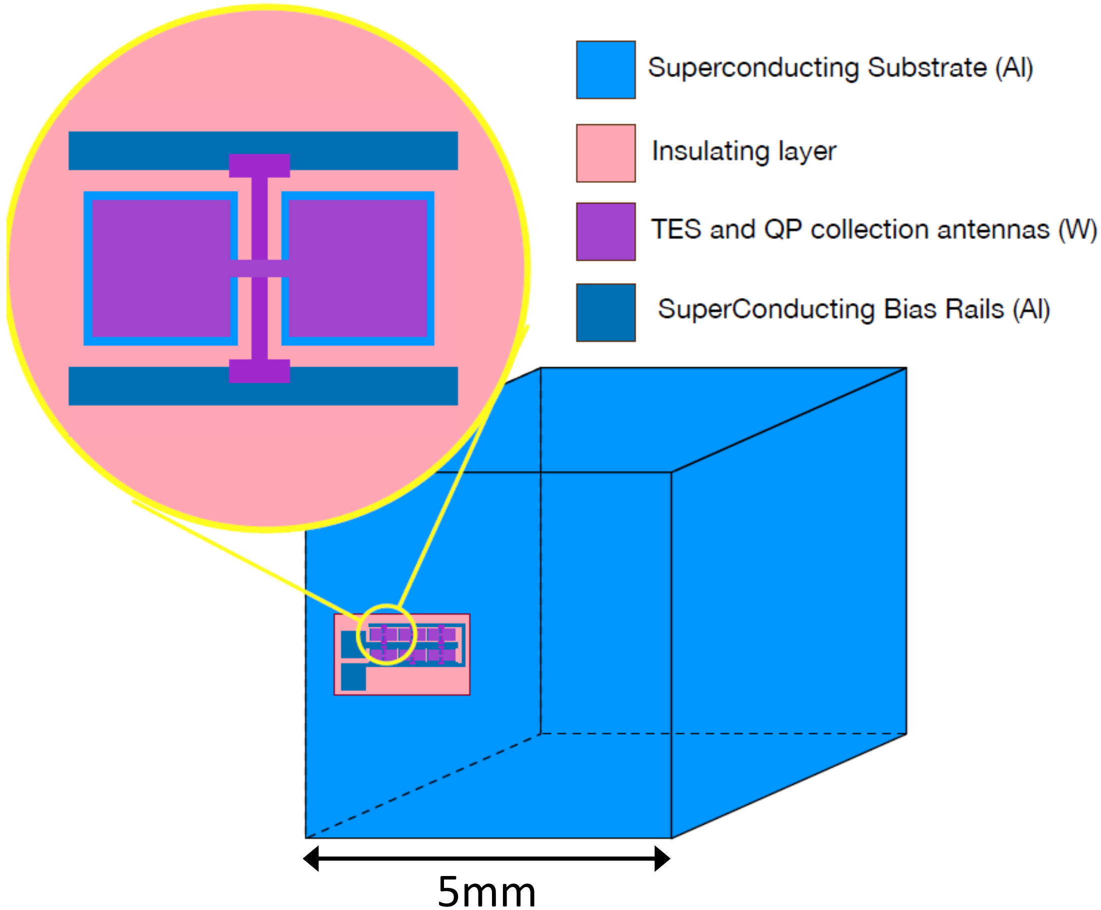


Design by Matt Pyle

Detector Concept

<u>Basic device idea:</u>
Large exposure but high energy resolution = excitation concentration

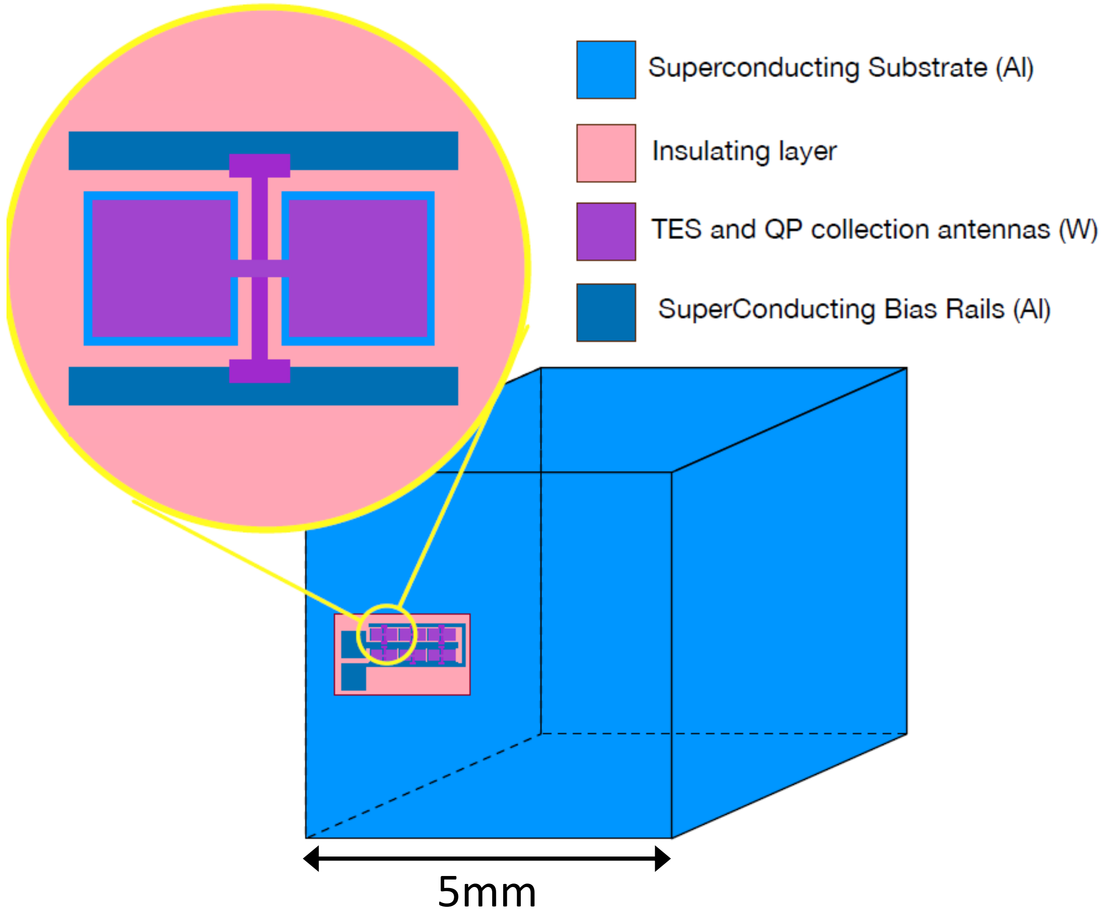
<u>To be efficient:</u>
absorber size of order elastic scattering length
+
long-lived excitations travel ballistically



Design by Matt Pyle

Detector Concept

- Excitation lifetime of order a milisecond
- With velocity $10^{-2}c$, plenty of time to random walk and get absorbed before recombine

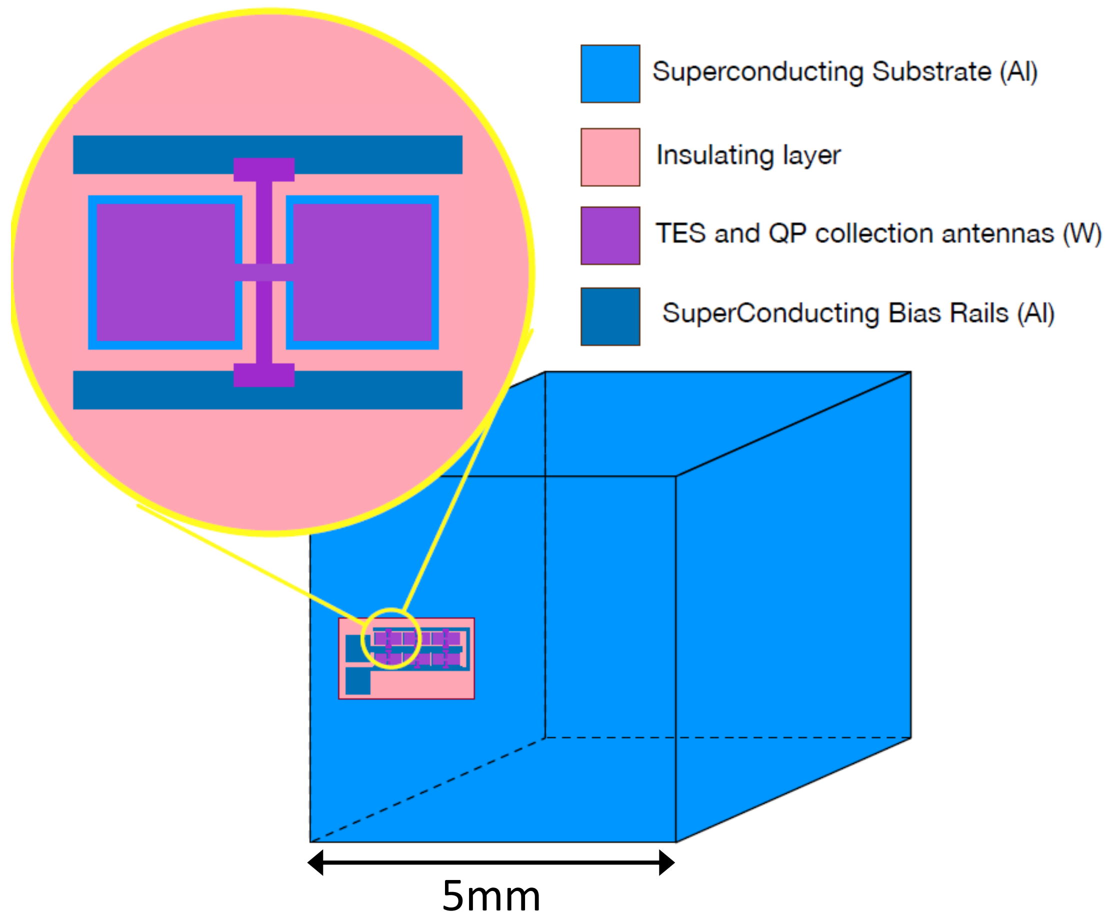


Design by Matt Pyle

Detector Concept

<u>Comments:</u>

- Low energy deposits: gapless absorber such as a metal
- But better -- metal in superconducting phase:
  - gap controls the thermal noise
  - makes excitations long lived → easier to collect



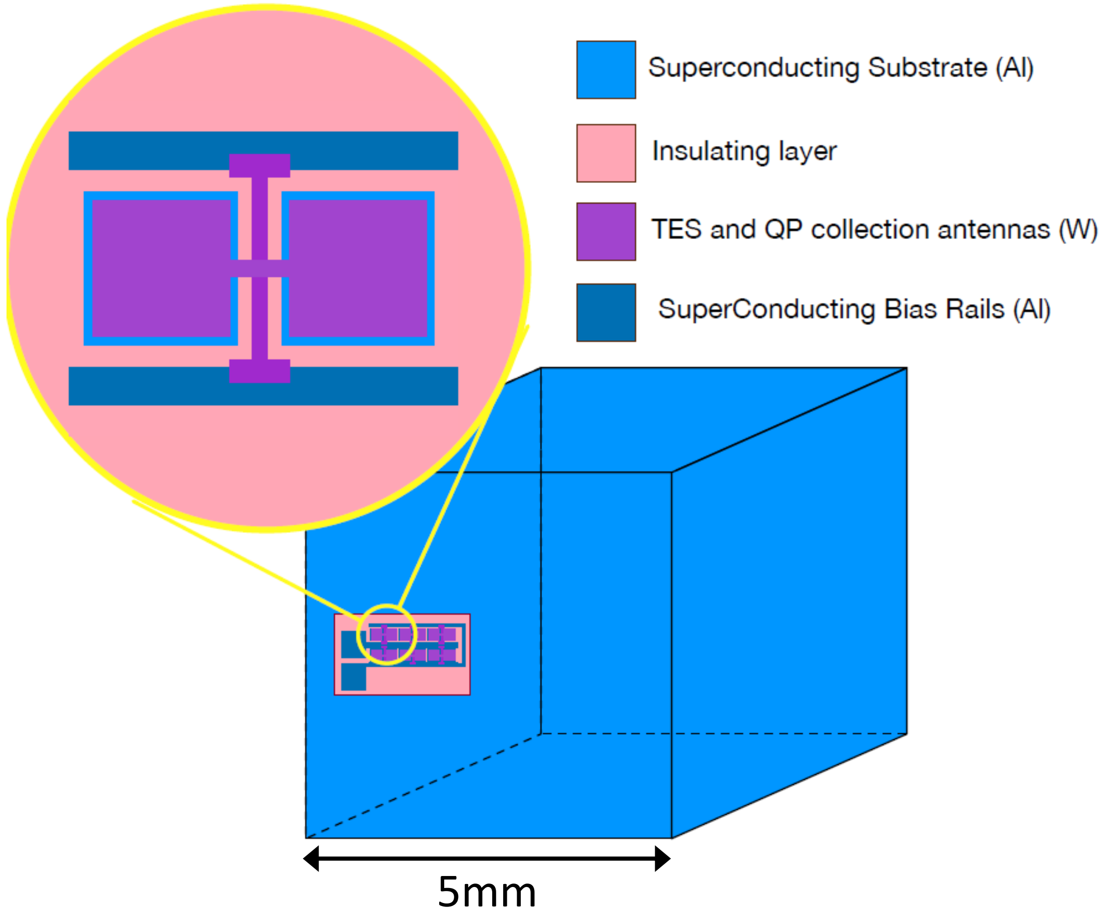
Design by Matt Pyle

Detector Concept

Comments:

- Initial excitation → 60% quasiparticles, 40% athermal phonons

- Design for collection of either



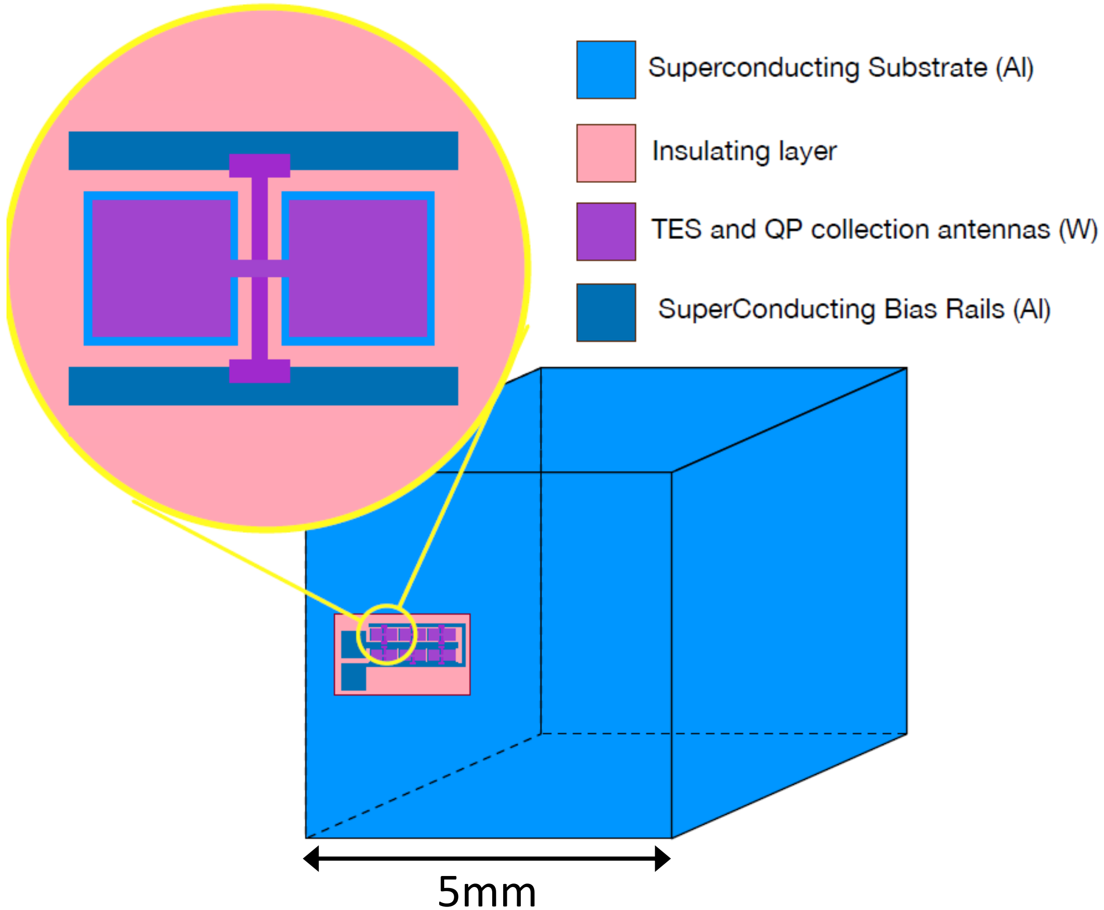
Design by Matt Pyle

		Quasiparticle Detector	Athermal Phonon Detector
	Number of Detectors	750	750
		Aluminum Absorber	Tantalum Absorber
	Absorber Volume	$5 \times 5 \times 5$ mm^3	$5 \times 5 \times 5$ mm^3
	Excitation Scattering Length	> 5 mm (> 2 mm [32])	> 5 mm
	Excitation Lifetime	20 ms (> 2 ms [33])	1.2 ms (1250 surface bounces)
$f_{\rm cascade}$	Fraction of Recoil Energy in Excitation System	$\sim 60\%$	$\sim 95\%$ (all QP have recombined [33])
	Characteristic Group Velocity	$\sim 2 \times 10^{-3}$	10^{-5}
		Tungsten QP Collector	Aluminum Phonon Collector
$A_{\rm collect}$	Total Area of All Collection Fins on a Detector	$12 \times 225\ \mu$m^2	2×0.21mm^2
$h_{\rm collect}$	Thickness of Collection Fins	$\sim$150 nm	$\sim$ 900 nm
$f_{\rm trap}$	Excitation Trapping Fraction	0.1	0.5 [51]
$\tau_{\rm collect}$	Excitation Collection Time	3 ms	700 μs
$f_{\rm collect}$	Excitation Collection Efficiency	87%	63%
$f_{\rm E\,Remain}$	Fraction of Potential Energy Remaining After Collection	~ 0.90	0.60×0.65
		Tungsten TES	Tungsten TES
	Number of TES per detector	6	2
$V_{\rm TES}$	Total Volume of all TES on a detector	$6 \times 1\mu$m$\times 20\mu$m$\times 35$nm	$2 \times 1\mu$m$\times 20\mu$m$\times 35$nm
T_c	Transition Temperature	9 mK	9 mK
$C_{\rm TES}$	Heat Capacity	1.0×10^{-17} J/K	4.0×10^{-18} J/K
α	Dimensionless Sensitivity	30	30
	Bias Power	7.0×10^{-20} W	2.8×10^{-20} W
$\sqrt{S_{\rm p,tot}(0)}$	Total Power Noise	4.4×10^{-22} W/$\sqrt{\rm Hz}$	2.8×10^{-22} W/$\sqrt{\rm Hz}$
$\tau_{\rm eff}$	Sensor Fall-Time	10 ms	10 ms
	Collector to TES Efficiency	1	0.74
$\sigma_{\rm E\,TES}$	TES Energy Resolution	0.3 meV	0.2 meV
$\sigma_{\rm E\,D}$	Detector Recoil Resolution $=\sigma_{\rm E\,TES}/(f_{\rm E\,Remain} f_{\rm collect} f_{\rm cascade})$	0.6 meV	0.7 meV
	Energy Threshold ($6\ \sigma_{\rm E\,D}$)	3.9 meV	4.2 meV

Detector Concept

Comments:

- Initial excitation → 60% quasiparticles, 40% athermal phonons
- Design for collection of either
- **Proof of concept**

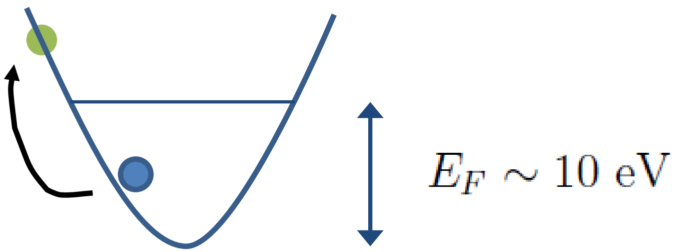


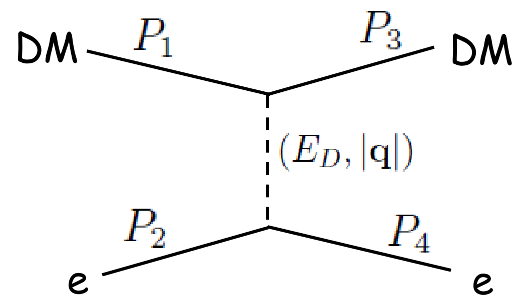
Design by Matt Pyle

Rates

Rates

Scatter off electrons in Fermi-degenerate metal – Pauli blocking





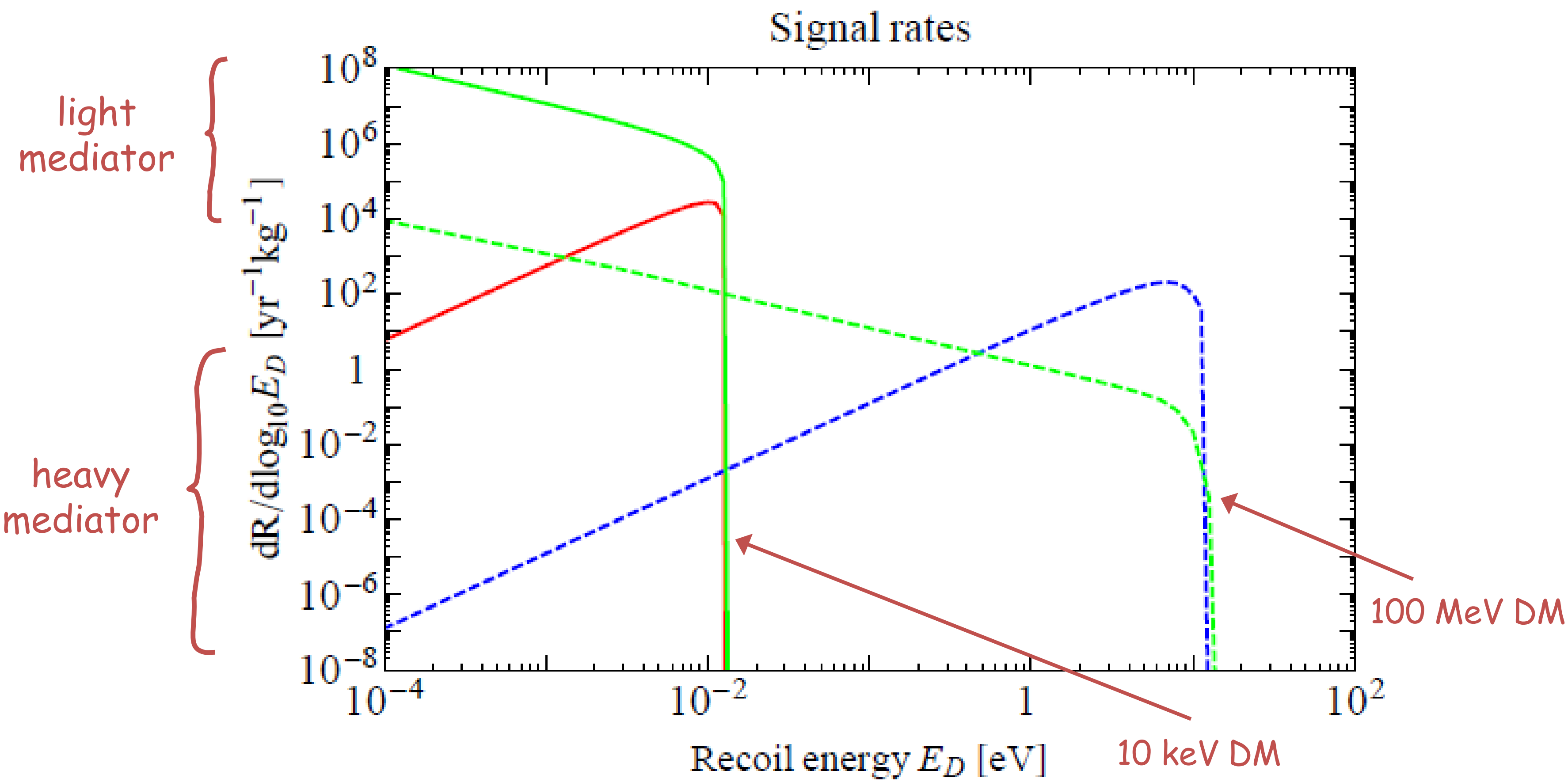
$$\langle n_e \sigma v_{\rm rel} \rangle = \int \frac{d^3 p_3}{(2\pi)^3} \frac{\langle |\mathcal{M}|^2 \rangle}{16 E_1 E_2 E_3 E_4} S(E_D, |\mathbf{q}|)$$

$$S(E_D, |\mathbf{q}|) = 2 \int \frac{d^3 p_2}{(2\pi)^3} \frac{d^3 p_4}{(2\pi)^3} (2\pi)^4 \delta^4 (P_1 + P_2 - P_3 - P_4) \times f_2(E_2)(1 - f_4(E_4))$$

Fermi-Dirac distribution

Pauli blocking $\sim \frac{E_D}{E_F} \sim 10^{-4}$

Rates



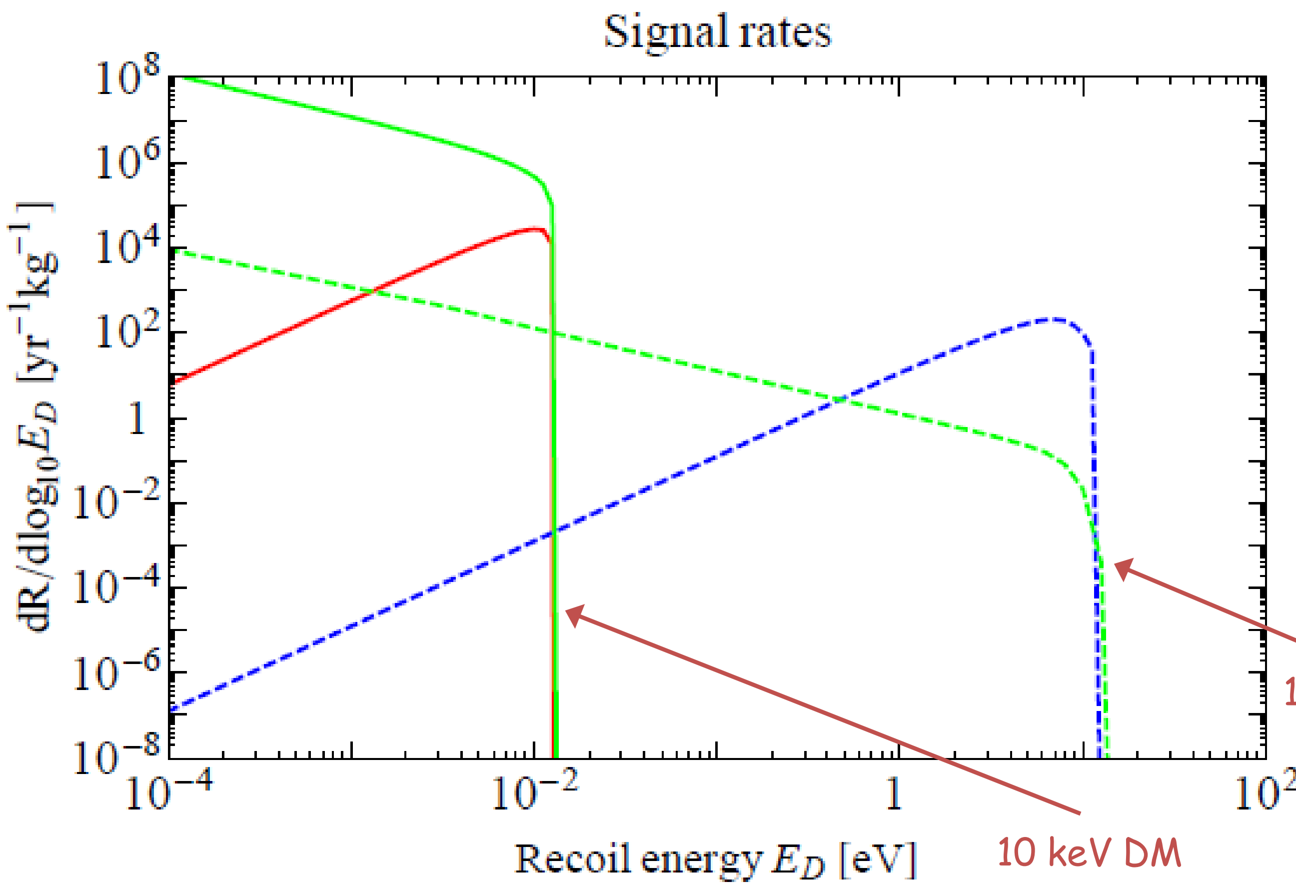
Signal rates
light
mediator
heavy
mediator
dR/dlog$_{10}E_D$ [yr^{-1}kg^{-1}]
10^8
10^6
10^4
10^2
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-4}
10^{-2}
1
10^2
Recoil energy E_D [eV]
100 MeV DM
10 keV DM

Rates

Low momentum dominates

$$\sigma = \frac{16\pi\alpha_e\alpha_X}{(m_\phi^2 - q^2)^2}\mu_{eX}^2$$

Pauli blocking dominates

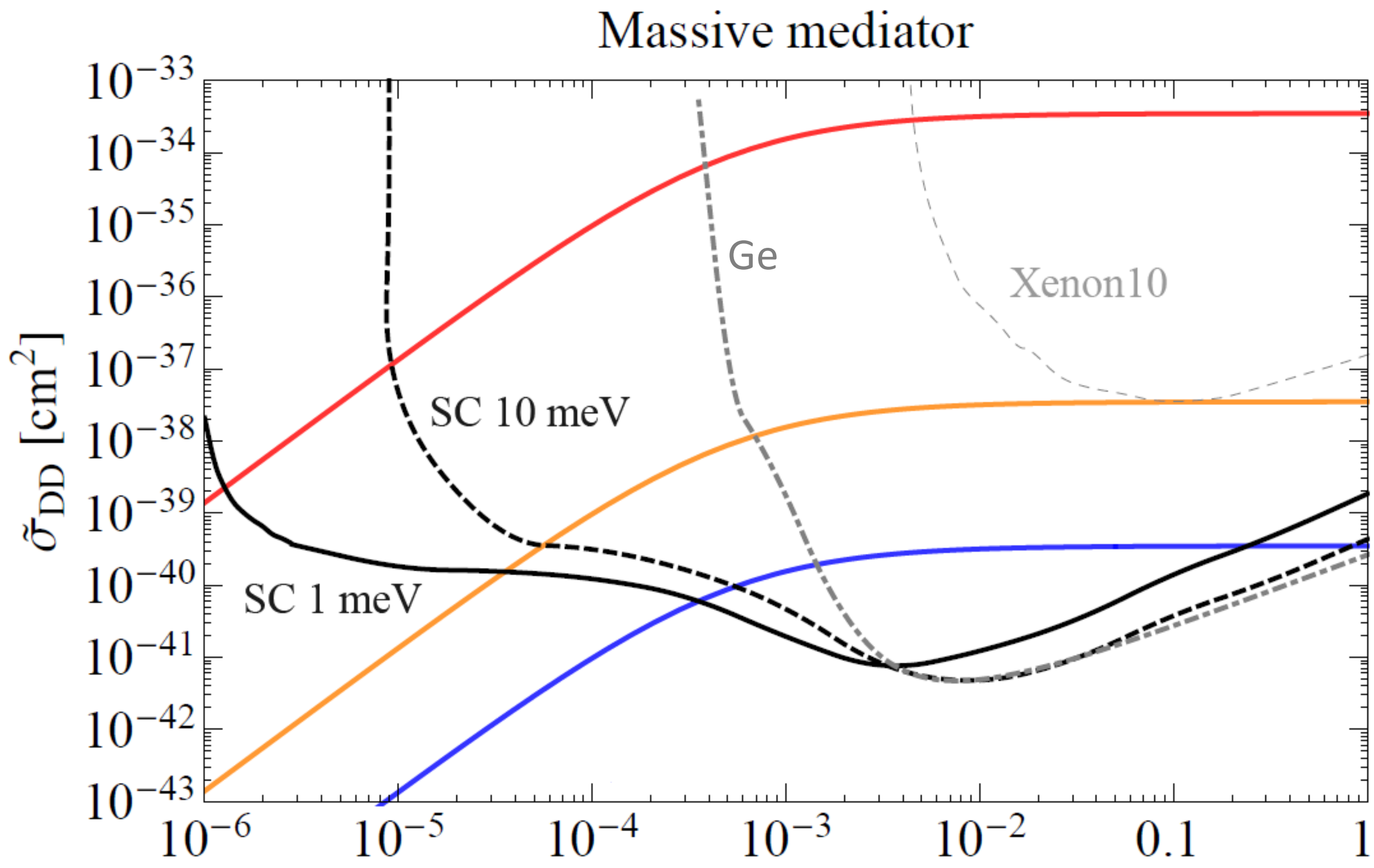


100 MeV DM

10 keV DM

Results

Reach

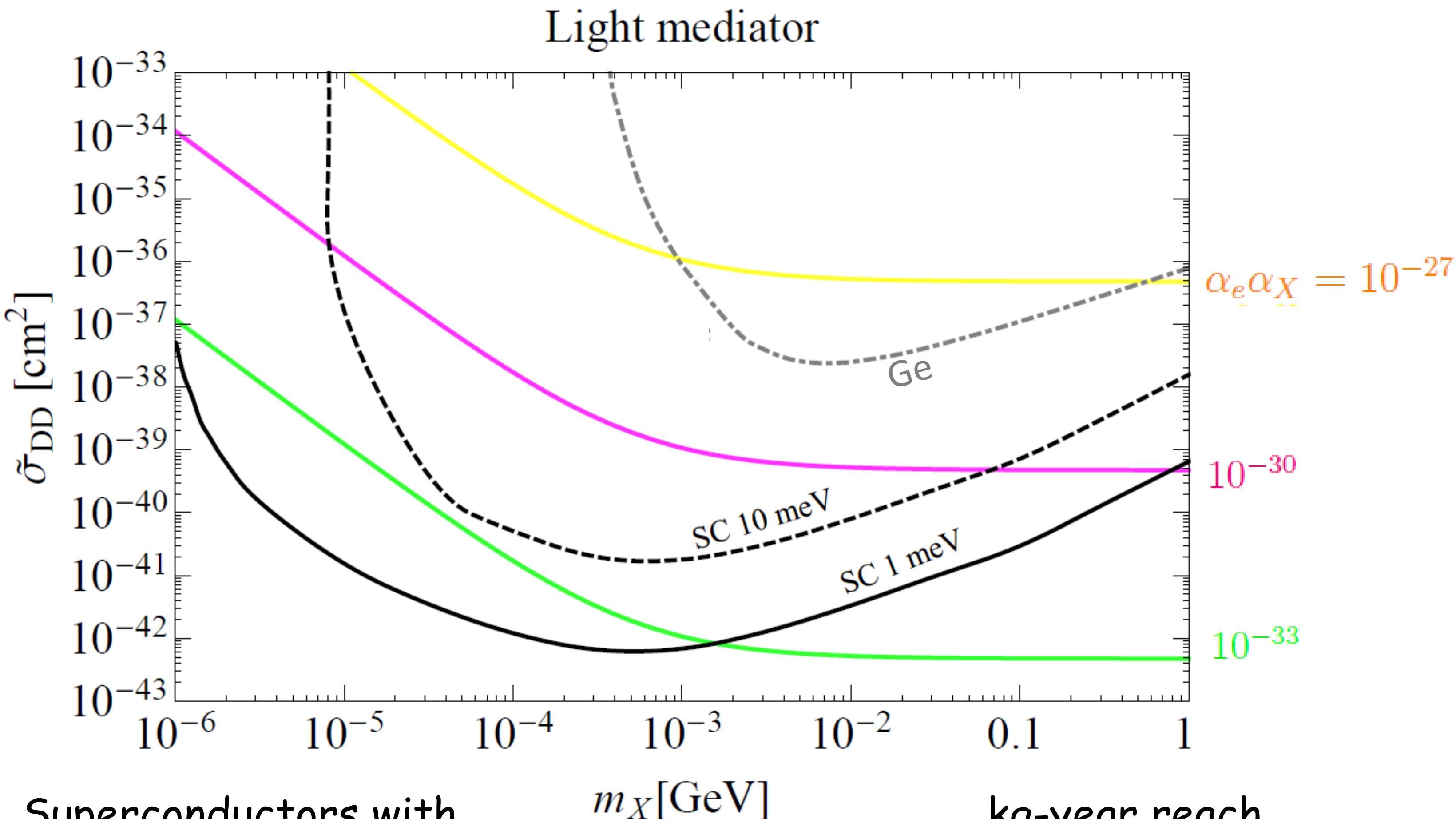


Superconductors with
1 meV or 10 meV
threshold

kg-year reach

$$\tilde{\sigma}_{\rm DD}^{\rm heavy} = \frac{16\pi\alpha_e\alpha_X}{m_\phi^4}\mu_{eX}^2$$

Reach



Superconductors with 1 meV or 10 meV threshold

kg-year reach

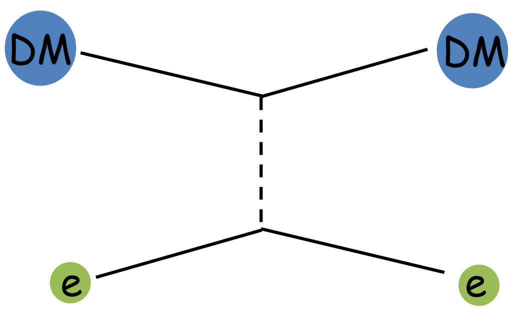
$$\tilde{\sigma}_{\rm DD}^{\rm light} = \frac{16\pi\alpha_e\alpha_X}{q_{\rm ref}^4}\mu_{eX}^2$$

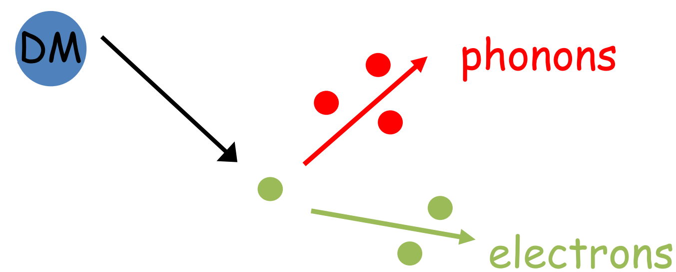
$$q_{\rm ref} \equiv \mu_{eX}v_X$$

Absorption vs. Scattering

Not only DM scattering – sensitive to DM absorption too

(Any target!)





$$E_D \sim \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 \sim 10^{-6} m_{\rm DM}$$

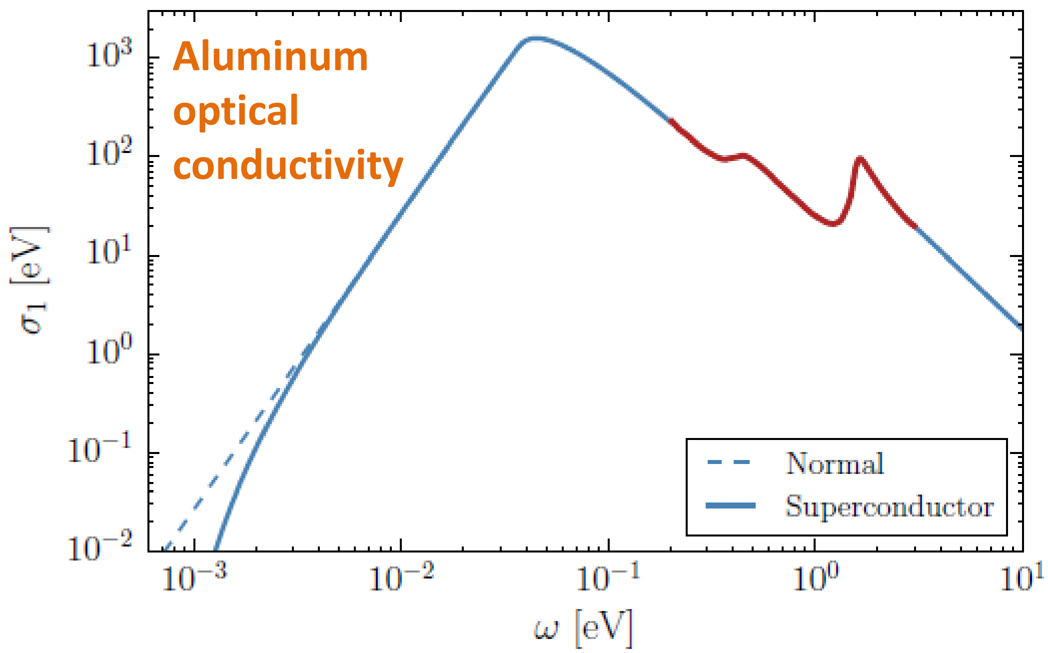
$$E_D \sim m_{\rm DM}$$

Absorption sensitive to much lighter DM masses

(see talk by Tongyan Lin on Friday)

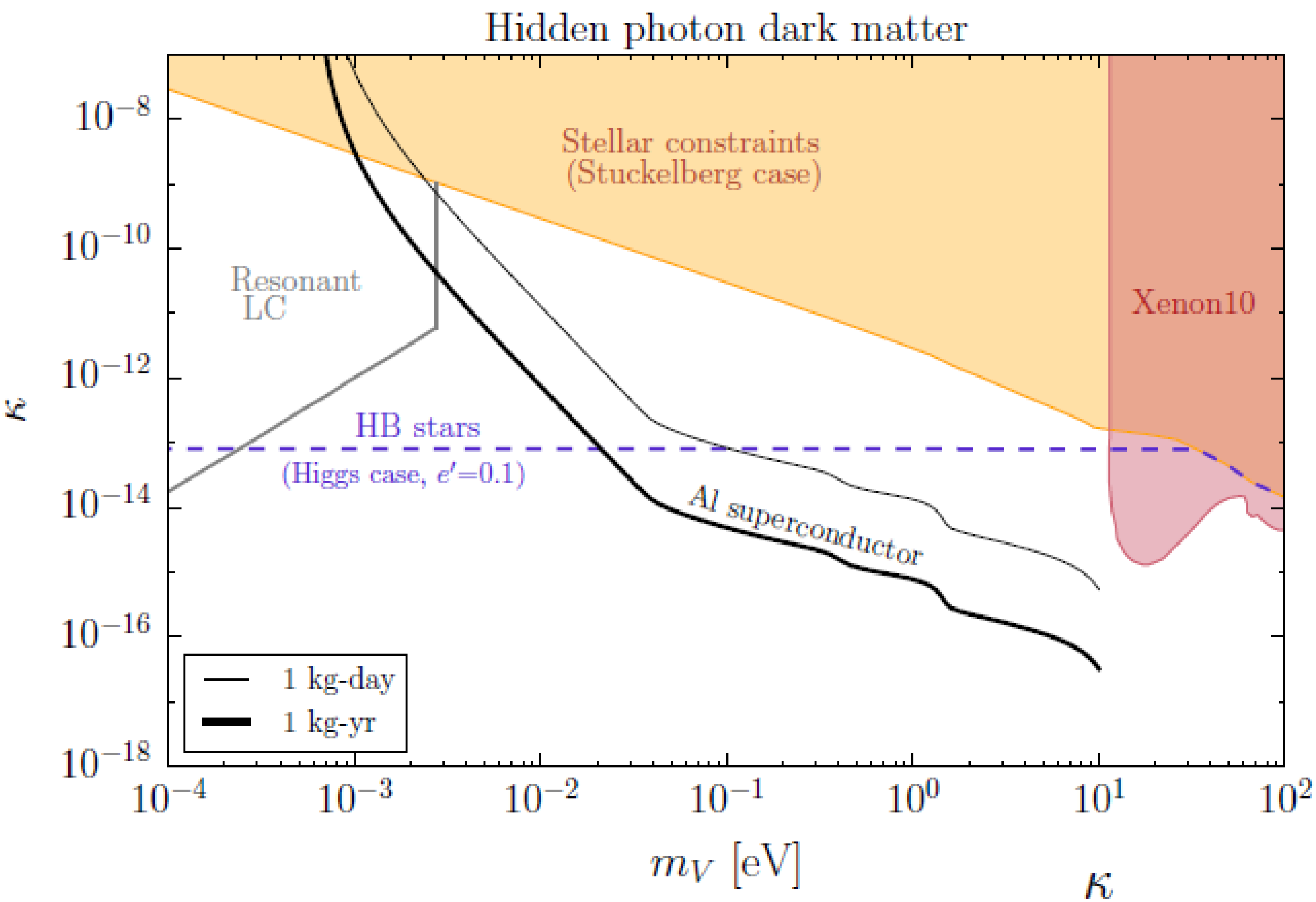
Absorption

Relate to optical properties of a given material

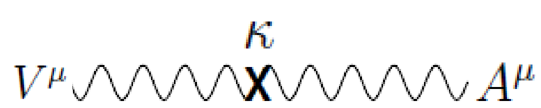


[**YH**, Lin and Zurek, PRD 2016]

Absorption



Kinetically mixed hidden photon



[**YH**, Lin and Zurek, PRD 2016]

Superconductors are super awesome.

Downside?

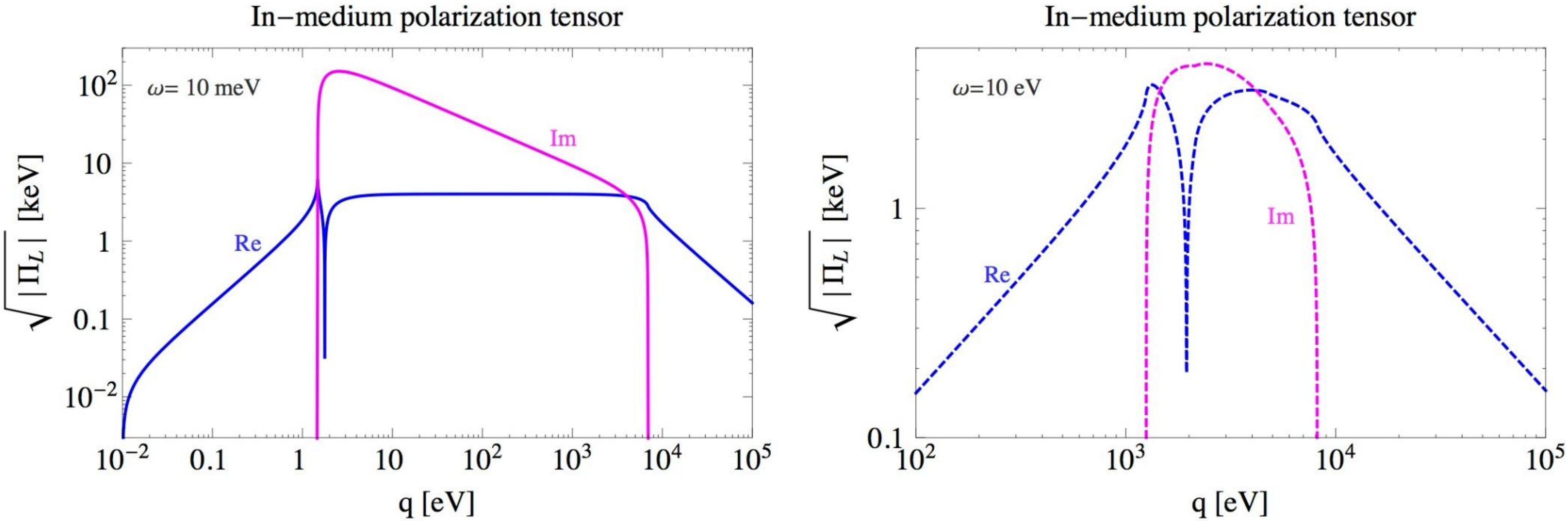
Metals are shiny

In-medium effects are substantial – photon picks up mass.

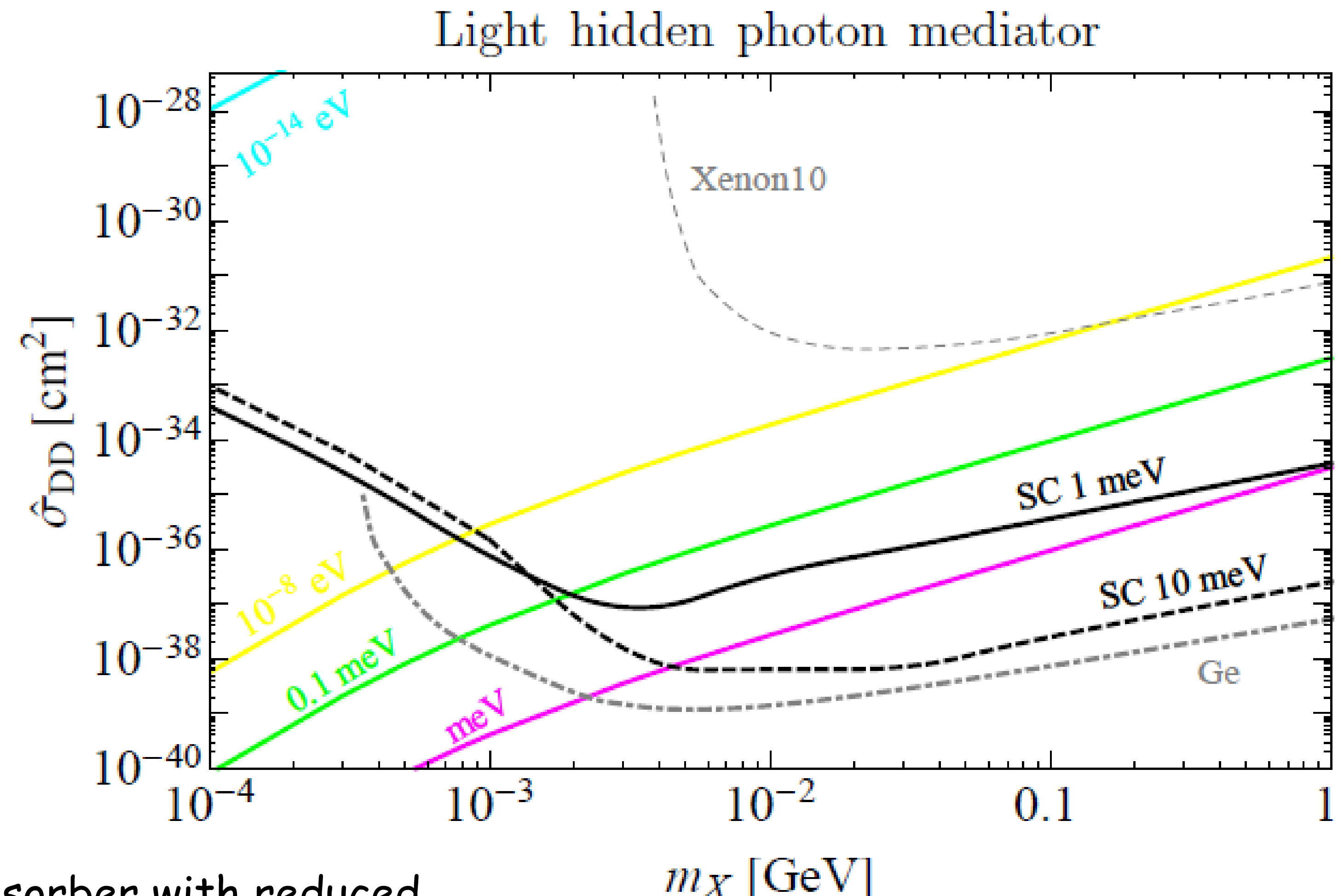
If kinetically-mixed hidden photon mediator:

$$\langle |\mathcal{M}|^2 \rangle \simeq \frac{16 m_e^2 m_\chi^2 g_\chi^2 e^2 \epsilon^2}{\left(q^2 - m_{A'}^2\right)^2 \left(1 - \Pi_L / |\mathbf{q}|^2\right)^2}$$

In-medium polarization tensor



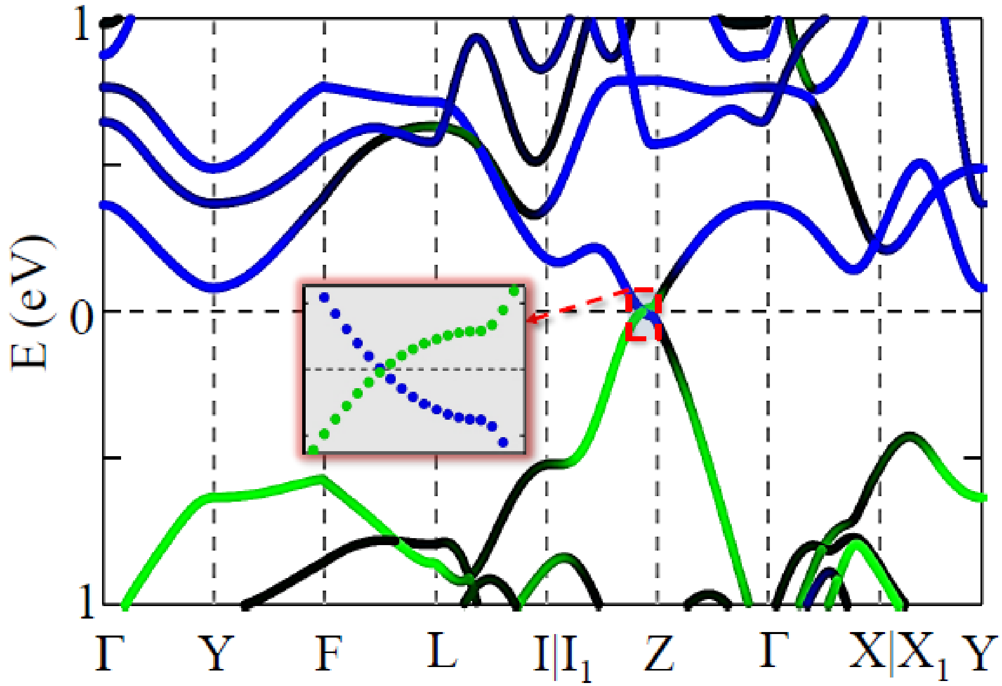
Kinetically mixed hidden photon

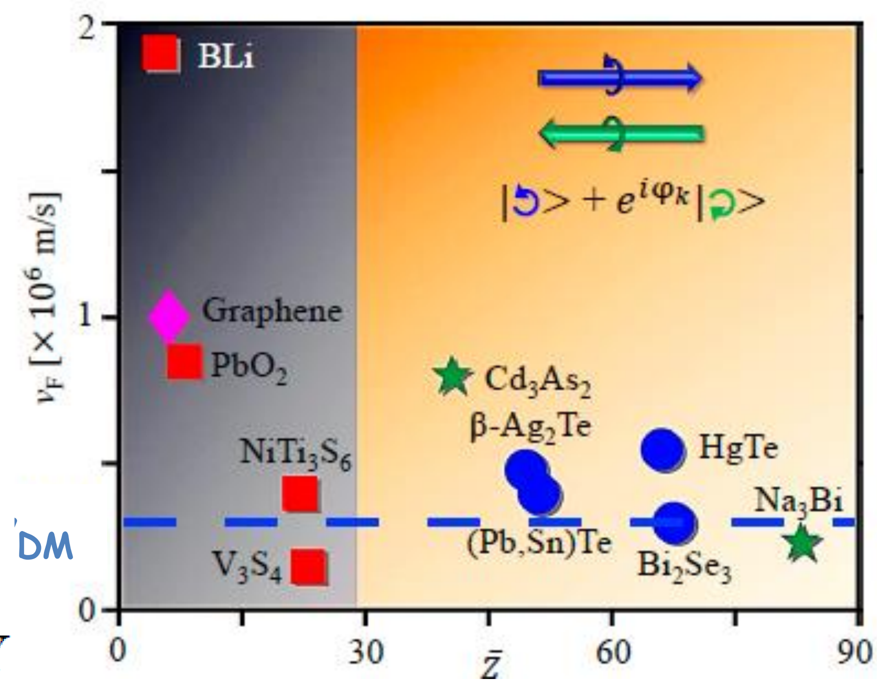


Absorber with reduced optical response would be better

$$\hat{\sigma}_{DD}^{\text{light/heavy}} \equiv \tilde{\sigma}_{DD}^{\text{light/heavy}} \times \left(\frac{q_{\text{ref}}}{\text{keV}}\right)^4$$

Semimetals =~ 3D graphene



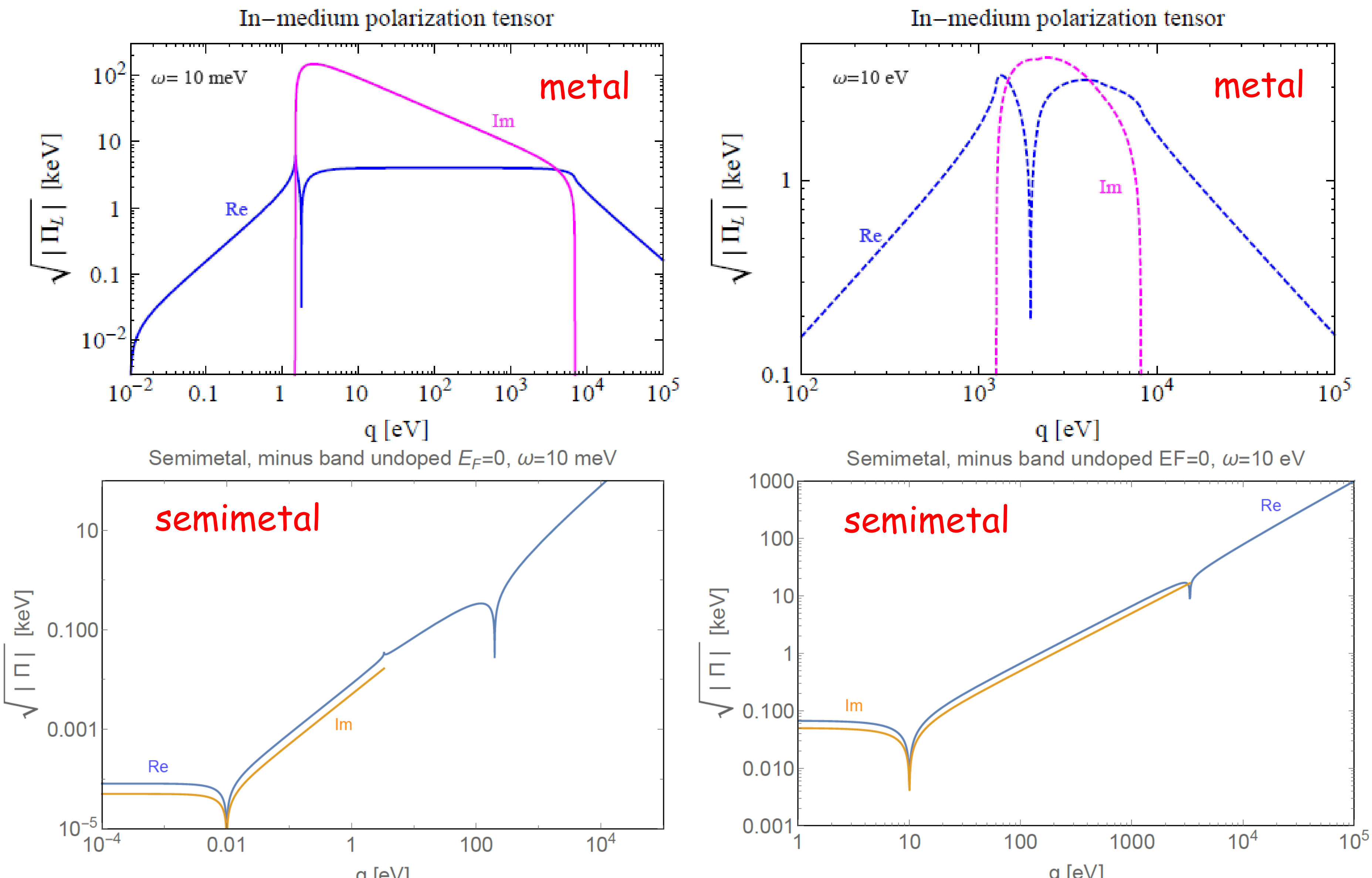


[Dolui and Das, 1412.2607]

Topological properties

Semimetals for light DM -- works in progress:
YH, Kahn, Lisanti, Neaton, Zurek….;
Grushin, **YH**, Ilan, Zurek

Optical response ('photon mass')



Summary

- Proposed new class of detectors using superconductors

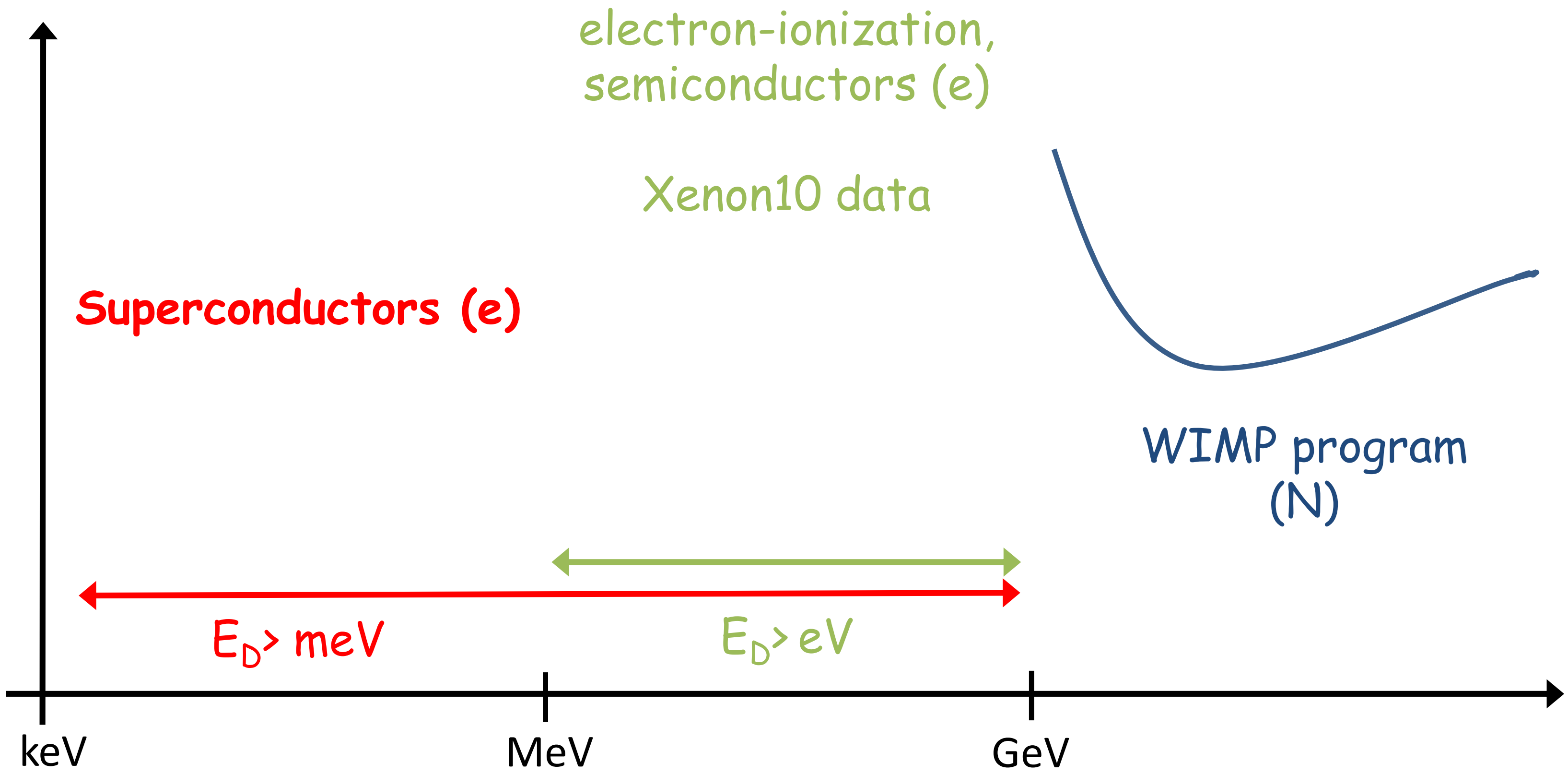
- Sensitive to O(meV) energy deposits →

  keV dark matter via scattering

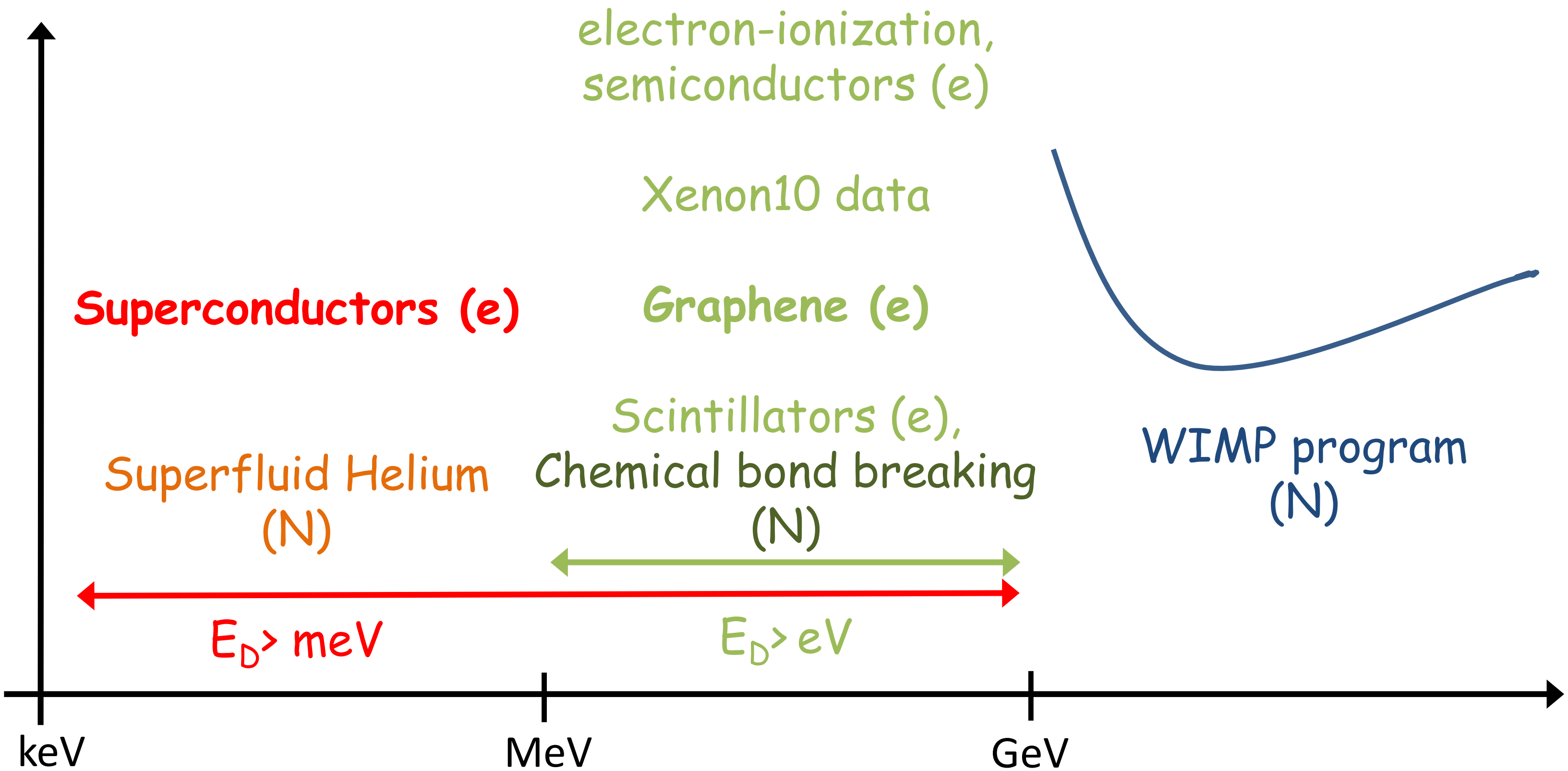
  meV dark matter via absorption

- R&D to lower noise such that O(meV) energies are detectable. (Port over everything being done now for semiconductors.)

Prospects

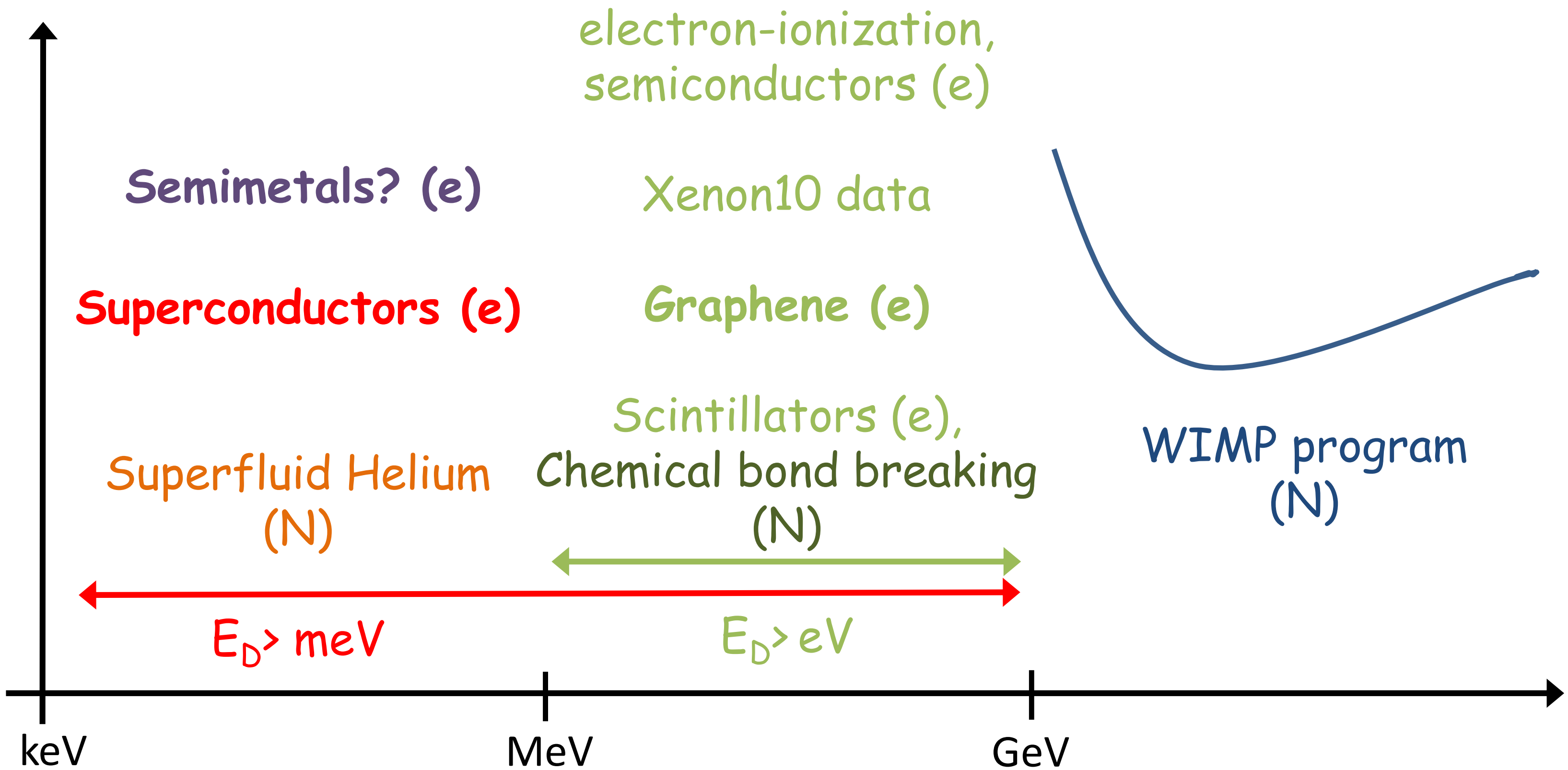

electron-ionization,
semiconductors (e)
Xenon10 data
Superconductors (e)
WIMP program
(N)
E_D> meV
E_D> eV
keV
MeV
GeV

Prospects



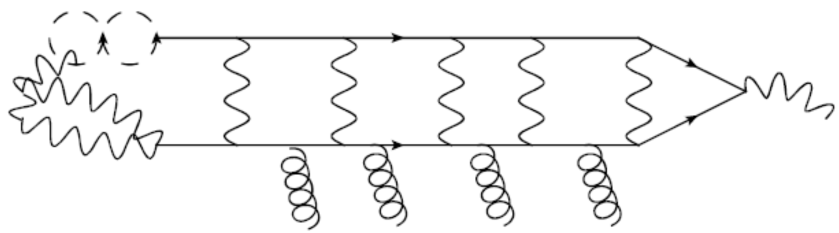
[**YH**, Zhao, Zurek 2015; **YH**, Zhao, Pyle, Zurek 2015; Schutz, Zurek 2014; **YH**, Kahn, Lisanti, Tully, Zurek 2016; Derenzo et al 2016; Essig et al 2016]

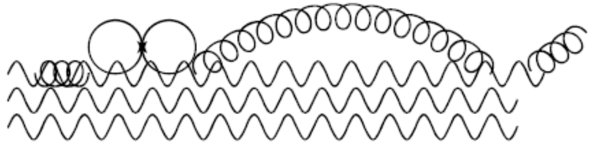
Prospects

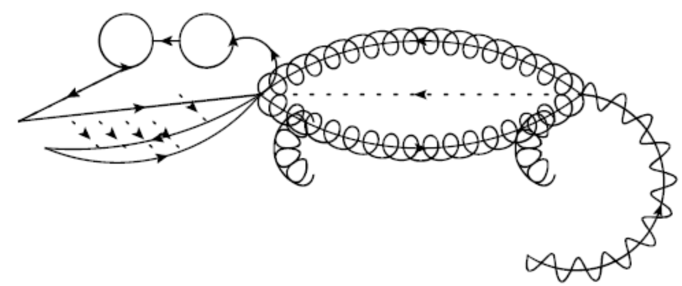


[**YH**, Khan, Lisanti, Neaton, Zurek…; Grushin, **YH**, Ilan, Zurek;
works in progress]

Thanks!



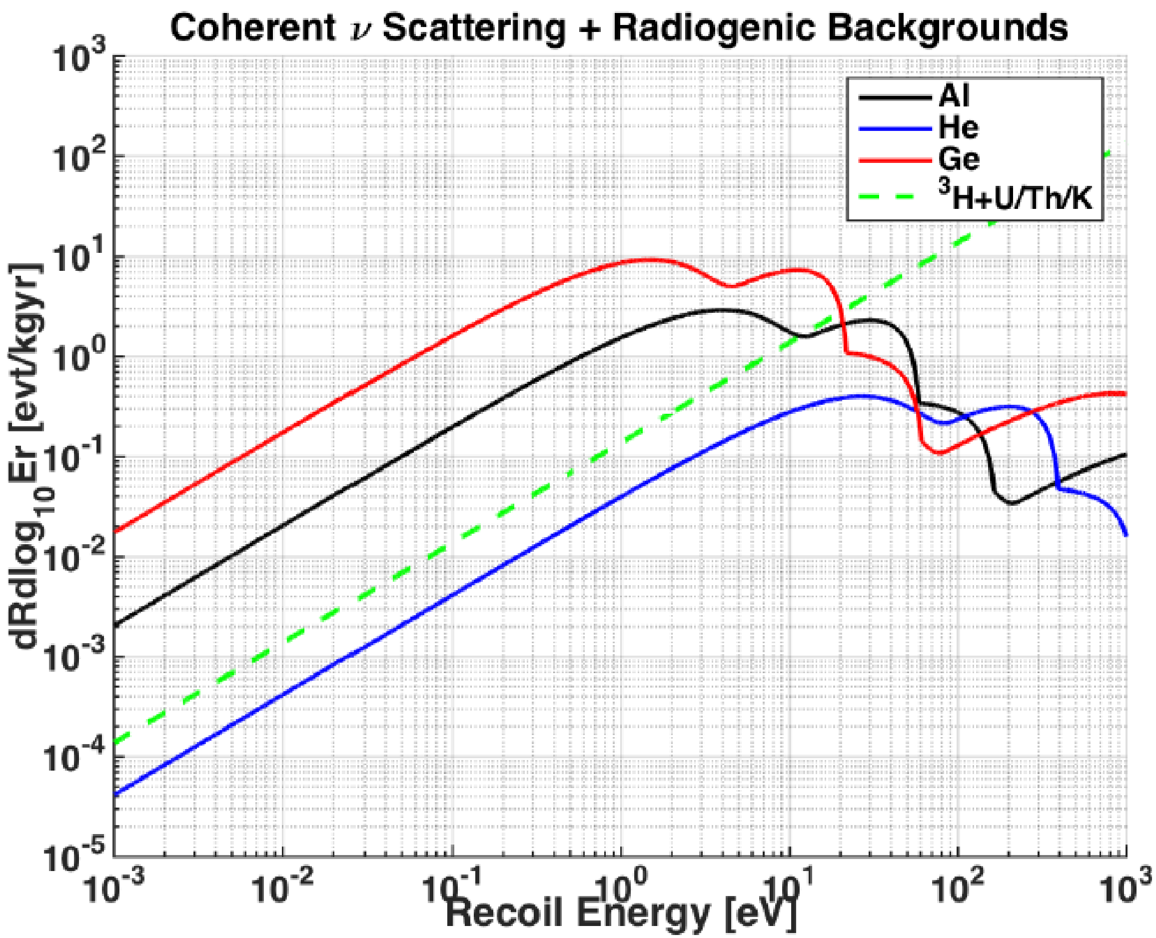




Backup

		Quasiparticle Detector	Athermal Phonon Detector
	Number of Detectors	750	750
		Aluminum Absorber	Tantalum Absorber
	Volume	$5 \times 5 \times 5$ mm^3	$5 \times 5 \times 5$ mm^3
	Excitation Scattering Length	> 5 mm (> 2 mm [31])	> 5 mm
	Excitation Lifetime	10 ms (> 2 ms [32])	1.2 ms (1250 surface bounces)
	Fraction of Recoil Energy in Excitation System	$\sim 60\%$	$\sim 95\%$ (all QP have recombined [32])
	Characteristic Group Velocity	$\sim 2 \times 10^{-3}$	10^{-5}
		Tungsten QP Collector	Aluminum Phonon Collector
	Number of Collection Fins	6×2	2×4
A_{collect}	Total Area of All Collection Fins	12×400 μm^2	2×0.21mm^2
h_{collect}	Thickness of Collection Fins	$\sim$150 nm	$\sim$ 900 nm
f_{trap}	Excitation Trapping Fraction	0.1	0.5 [50]
τ_{collect}	Excitation Collection Time	3.4 ms	700 μs
f_{collect}	Excitation Collection Efficiency	0.75	0.63
	Fraction of Energy Remaining After Collection	~ 0.90	0.60
		Tungsten TES	Tungsten TES
	Number of TES	6	1
V_{TES}	Total Volume of TES	$6\times 1\mu\mathrm{m} \times 24\mu\mathrm{m} \times 35\mathrm{nm}$	$2\times 1\mu\mathrm{m} \times 24\mu\mathrm{m} \times 35\mathrm{nm}$
T_c	Transition Temperature	9 mK	9 mK
C_{TES}	Heat Capacity	1.2×10^{-17} J/K	4.0×10^{-18} J/K
α	Dimensionless Sensitivity	20	20
	Bias Power	8.3×10^{-20} W	2.8×10^{-20} W
$\sqrt{S_{\mathrm{p,tot}}(0)}$	Total Power Noise	4.9×10^{-22} W/$\sqrt{\mathrm{Hz}}$	2.8×10^{-22} W/$\sqrt{\mathrm{Hz}}$
τ_{eff}	Sensor Fall-Time	10 ms	10 ms
	Collector to TES Efficiency	1	0.74
$\sigma_{\mathrm{E,TES}}$	TES Energy Resolution	0.4 meV	0.2 meV
$\sigma_{\mathrm{E,D}}$	Detector Recoil Resolution	0.9 meV	0.8 meV

Backgrounds

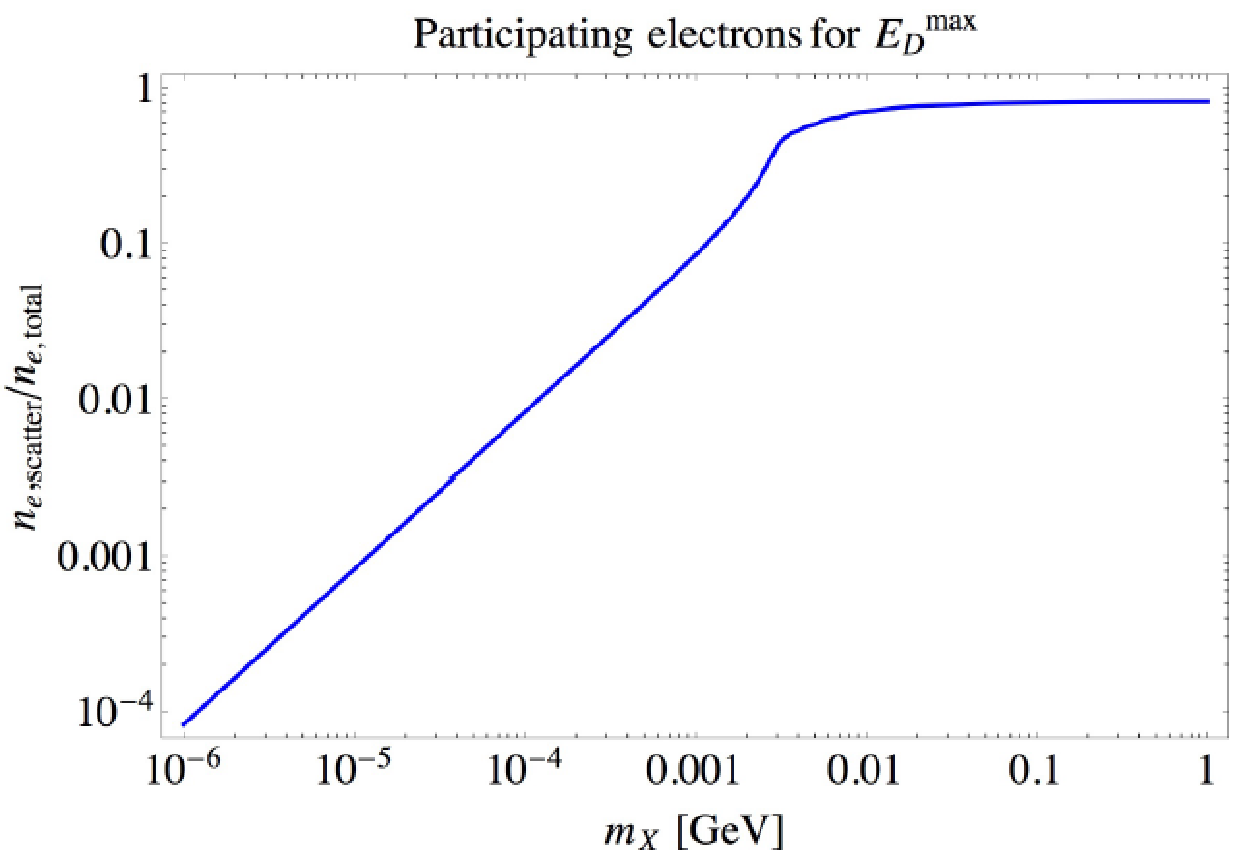


(pp neutrinos scattering on nuclei)

1meV – 1eV: less than 1 event/kg-yr

10meV-10eV: 3 events/kg-yr

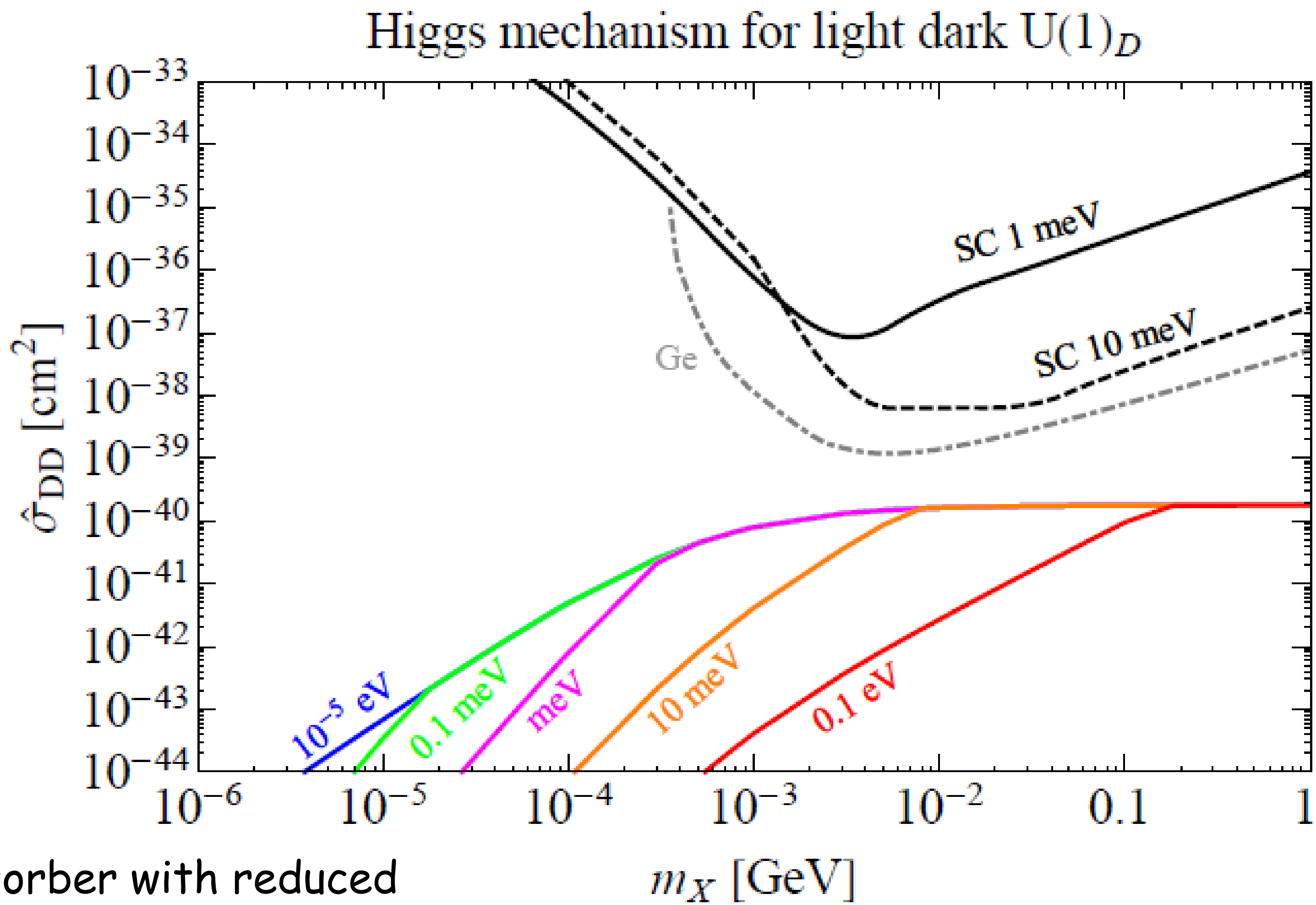
Pauli Blocking



Constraints

- Self-interactions of dark matter
- Stellar emission of light particles
- Kinetic decoupling @ recombination
- N_{eff}
- Terrestrial: beam dump, (g-2), low energy machines, ….

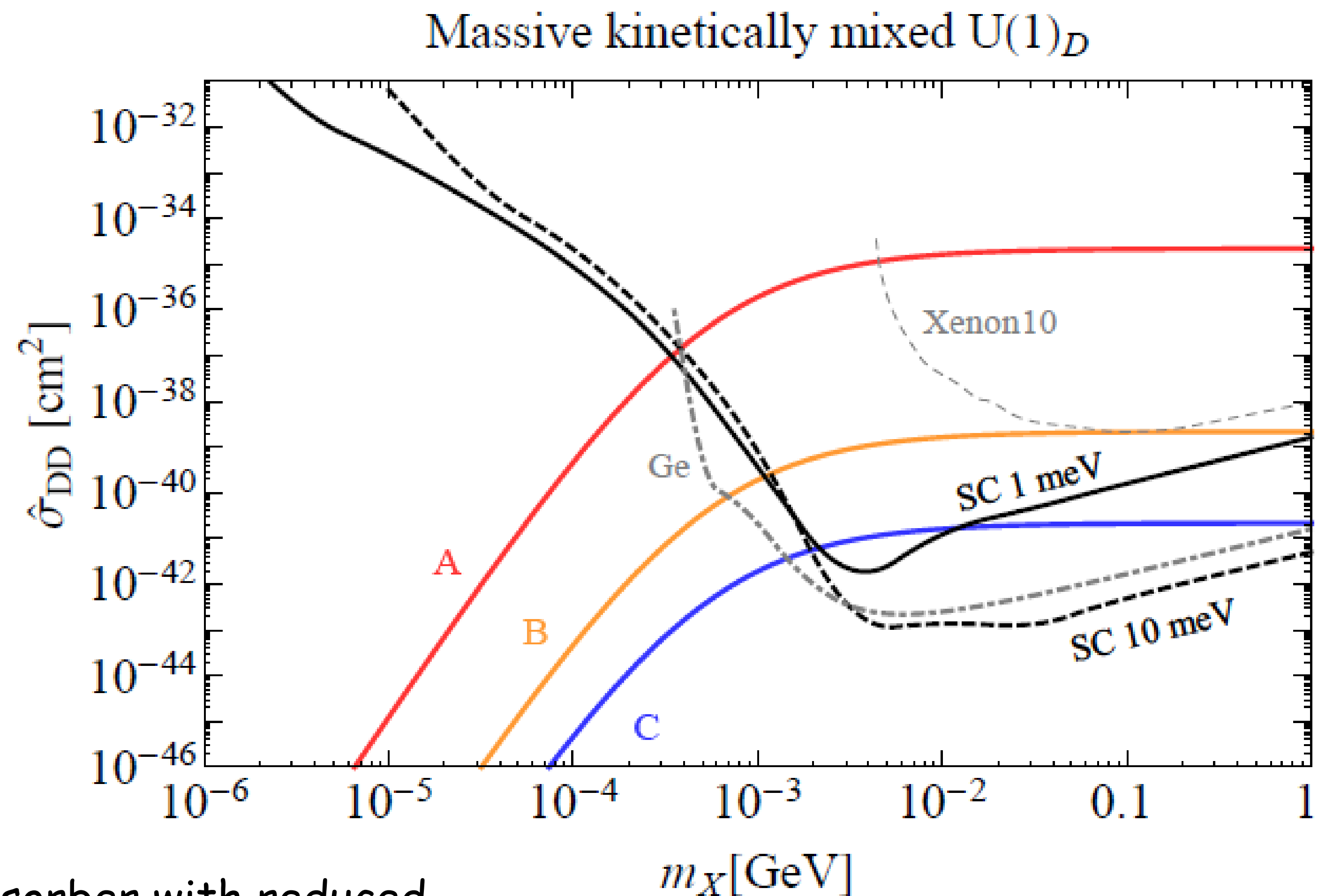
Kinetically mixed hidden photon



Absorber with reduced optical response would be better

$$\hat{\sigma}_{\rm DD}^{\rm light/heavy} \equiv \tilde{\sigma}_{\rm DD}^{\rm light/heavy} \times \left(\frac{q_{\rm ref}}{\rm keV}\right)^4$$

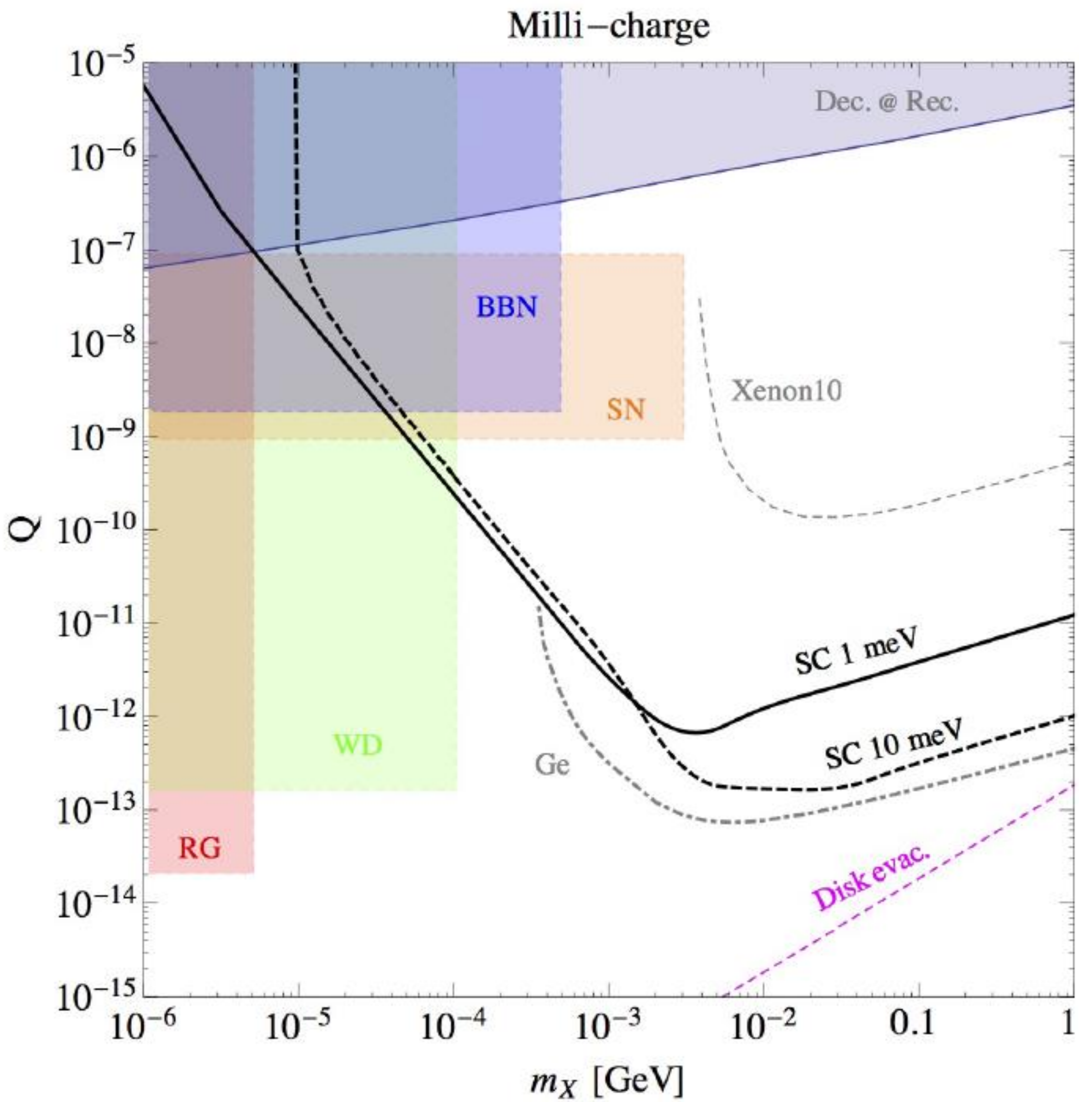
Kinetically mixed hidden photon



Absorber with reduced optical response would be better

$$\hat{\sigma}_{\rm DD}^{\rm light/heavy} \equiv \tilde{\sigma}_{\rm DD}^{\rm light/heavy} \times \left(\frac{q_{\rm ref}}{\rm keV}\right)^4$$

Milli-charged DM



Concentration & Collection

bounces until collected = $\frac{A_{\rm absorber}}{A_{\rm collect}}\frac{1}{f_{\rm trap}}$

$$\tau_{\rm collect} = \frac{4V_{\rm absorber}}{\langle|v|\rangle A_{\rm collect}}\frac{1}{f_{\rm trap}}$$

excitation collection efficiency = $f_{\rm collect} = \frac{\tau_{\rm life}}{\tau_{\rm life}+\tau_{\rm collect}}$

$$n_e = \frac{(E_F m_e)^{3/2}}{3\pi^2}$$

$$\xi_0 = v_F/(\pi\Delta)$$

macroscopic correlation length, ~micron

Some Constraints

- Self-interactions: $$\frac{\sigma_T}{m_X} \lesssim 1 - 10 \ \ \mathrm{cm}^2/\mathrm{g}$$

$$\sigma_T^{\mathrm{light}} \approx \frac{16\pi\ \alpha_X^2}{v^4 m_X^2} \ln \beta^{-1}, \quad \beta = \frac{2m_\phi \alpha_X}{m_X v^2} \ll 1$$

$$(\alpha_X)^{\mathrm{light}}_{\mathrm{SIDM}} \lesssim 4 \times 10^{-17} \left(\frac{m_X}{\mathrm{keV}}\right)^{3/2} \left(\frac{v}{10^{-4}}\right)^2 \left(\frac{58}{\ln \beta^{-1}}\right)^{1/2}, \quad \beta = \frac{2m_\phi \alpha_X}{m_X v^2}$$

- Decoupling @ recombination:

$$\Gamma_p = \sum_{b=e,p} \frac{8\sqrt{2\pi} n_b \alpha_X \alpha_b \mu_{bX}^{1/2}}{3 m_X T^{3/2}} \ln \left[\frac{3T\lambda_{\mathrm{cut}}}{\sqrt{\alpha_b \alpha_X}}\right]\Bigg|_{T=\hat{T}} \lesssim H|_{T=\hat{T}}$$

$$(\alpha_X \alpha_e)^{\mathrm{light}}_{\mathrm{kin.\ dec.}} \lesssim 10^{-19} \left(\frac{m_X / \sum_{b=e,p} \sqrt{\mu_{bX}}}{\mathrm{keV}^{1/2}}\right) \left(\frac{50}{\ln}\right)$$

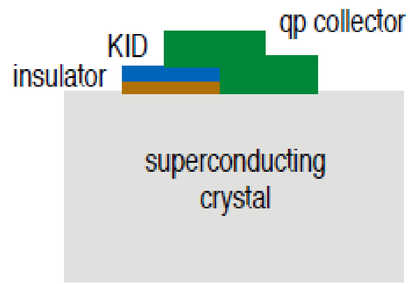
Some Constraints

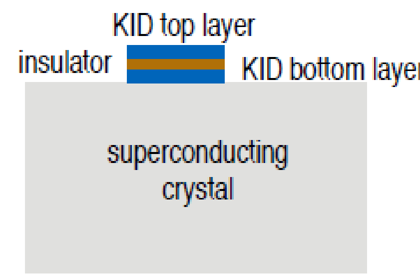
- Stellar: $g_e^{\rm brem} \lesssim 1.3 \times 10^{-14} \quad [\rm HB]$

(trapping in supernova releases $g_e \gtrsim 10^{-6}$)

$$\left(\begin{array}{l} \text{Kinetically mixed hidden photon} \quad 10^{-5}\ {\rm eV} \lesssim m_\phi \lesssim {\rm eV} \\ \\ \text{Higgstrahlung} : \quad \epsilon \left(\frac{q_{H_D} g_X}{0.1}\right) \lesssim 8 \times 10^{-14} \quad [\rm HB]\,, \\ \text{Resonance conversion} : \quad \epsilon \left(\frac{m_{A'}}{\rm eV}\right) \lesssim 4 \times 10^{-12} \quad [\rm Sun]\,, \end{array} \right)$$

What About Direct Quasiparticle Creation?

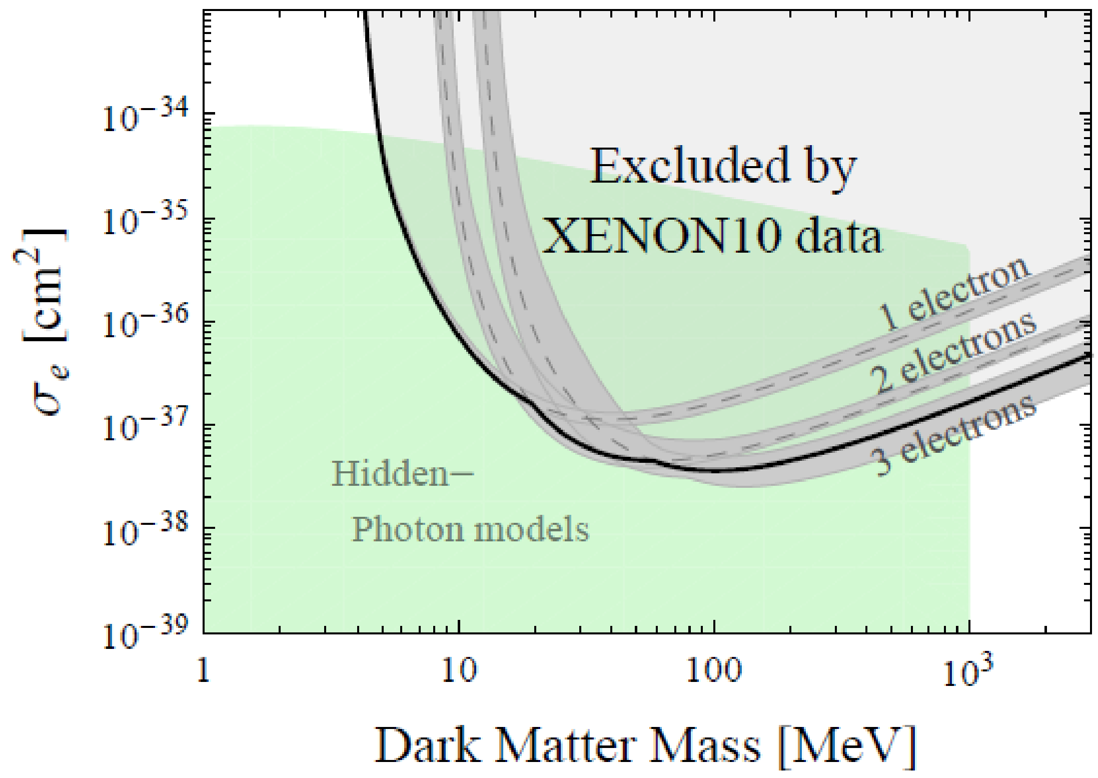




- Long scattering length superconducting crystal: qp's diffuse
- Architectures:
  - KID on insulator, qps collected via thick superconducting film
    - Technically straightforward to imagine a design:
    - Avoids having to deal with operating KID on superconductor
    - Requires good trapping: qps from crystal into collector film, from collector film into KID
      - Problem: fast trapping require large Δ ratio; large Δ ratio → lots of energy lost to phonon emission
      - Maybe still ok if just interesting in counting substrate qps (still can get meV threshold)
  - KID on crystal
    - Need to avoid short-circuiting KID: microstrip structure?
    - Film needs to be thick to avoid being proximitized by crystal (Δ_{KID} pulled to $\Delta_{crystal}$)
- No obvious advantage over phonon mediation *for NR detection*
  - Phonons already provide sensitivity to meV scale
  - KIDs are already pair-breaking detectors: insensitive to sub-gap phonons in principle
- But definitely interesting for electron scattering

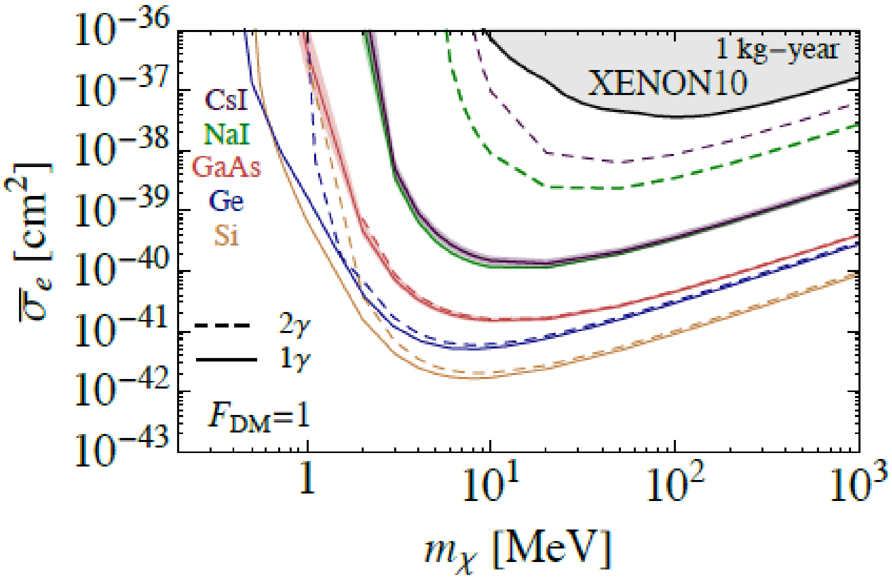
Xenon10 data

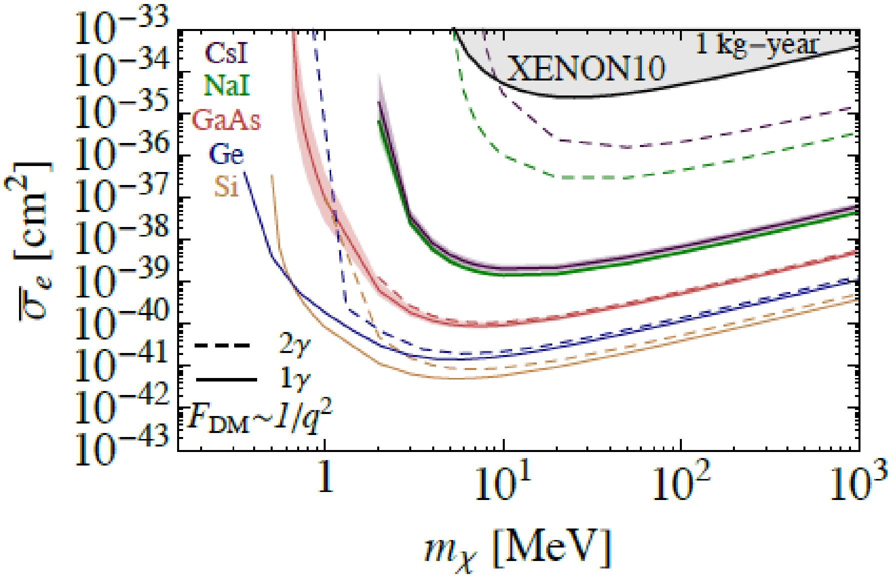
Sub-GeV dark matter -- look for electron ionization signals



[Essig, Manalaysay, Mardon, Sorensen, Volansky, PRL 109, 021301 (2012)]

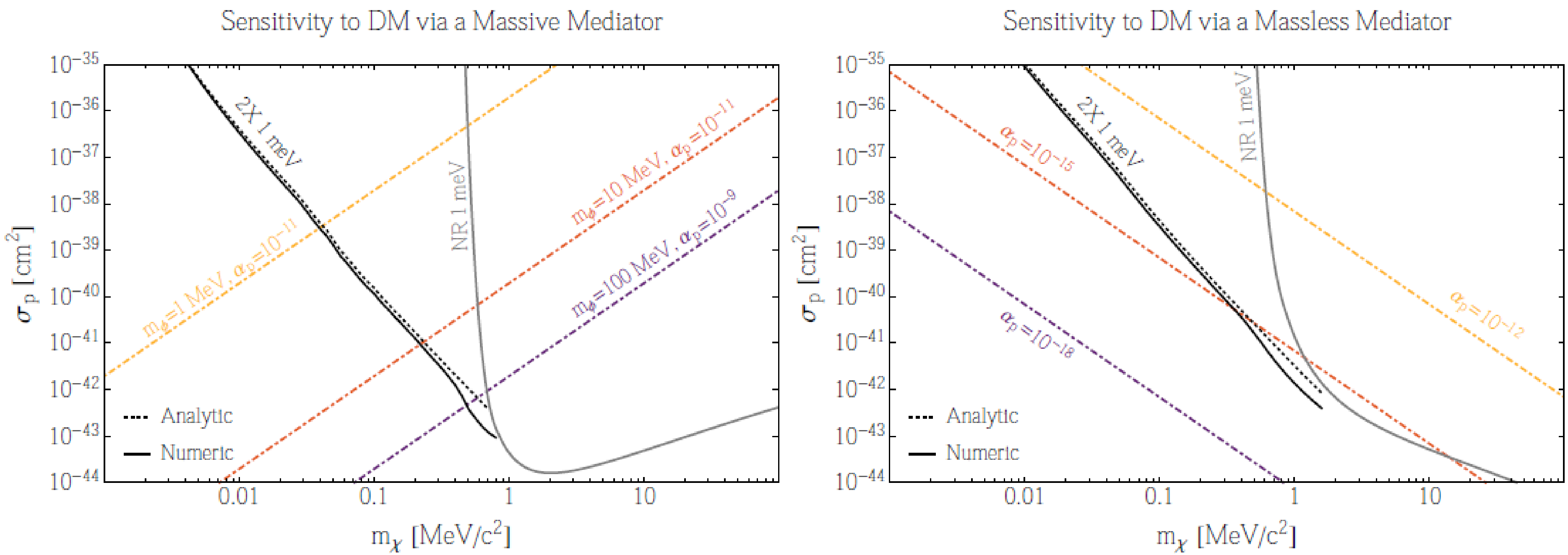
Scintillators





[Derenzo et al, 1607.01009]

Superfluid Helium

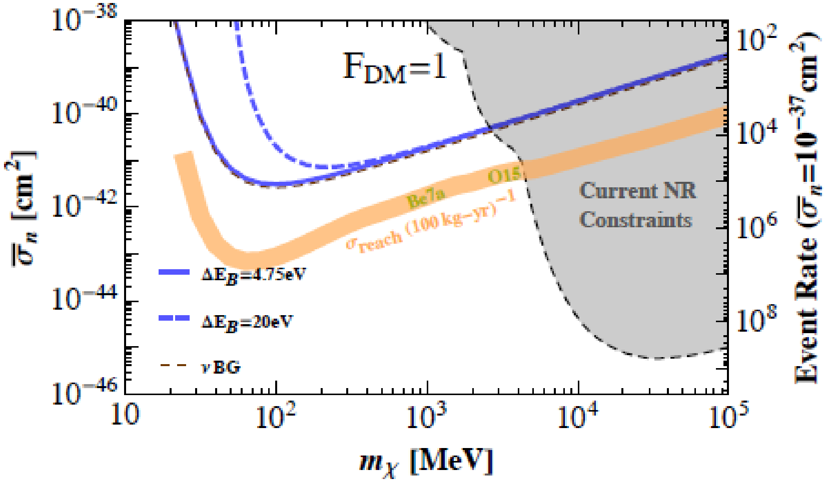


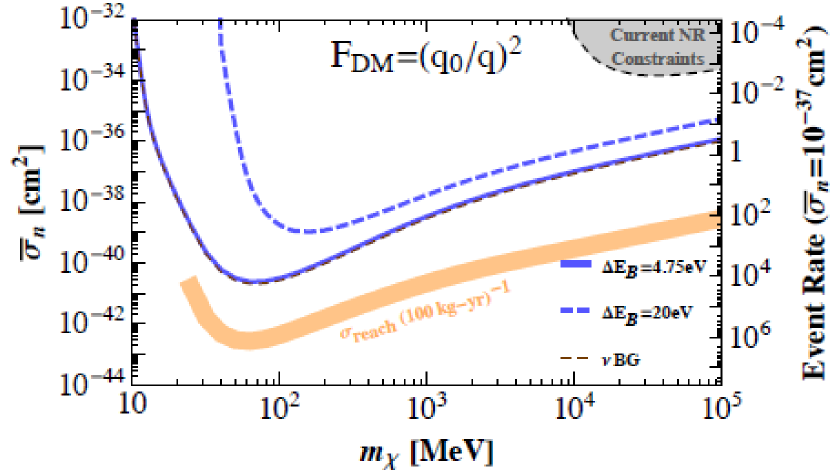
[Schutz and Zurek, 1604.08206]

[Essig, Mardon, Slone, Volansky, 1608.02940]

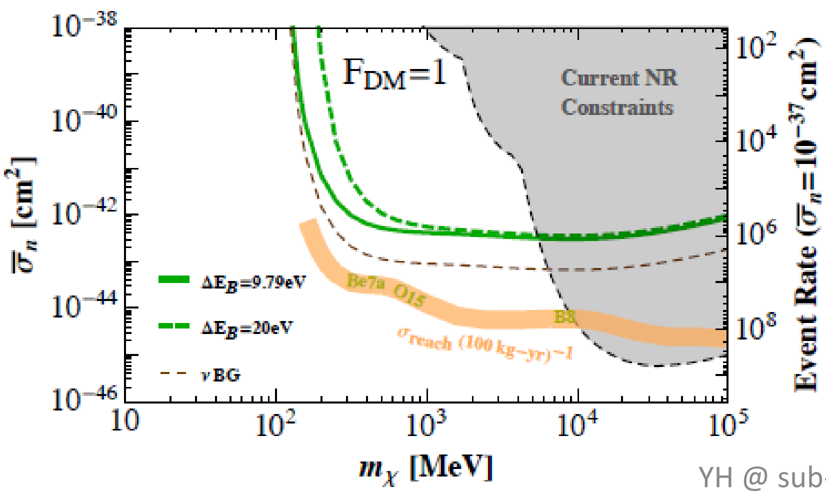
Chemical Bond Breaking

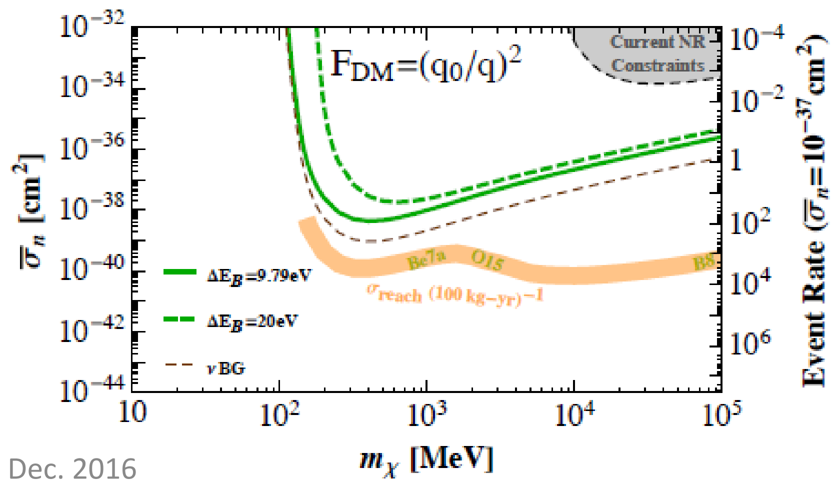
H$_2$-like Molecule



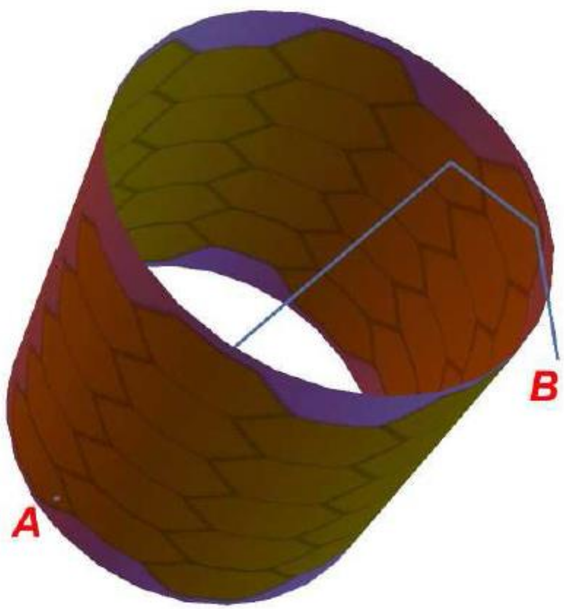


N$_2$-like Molecule

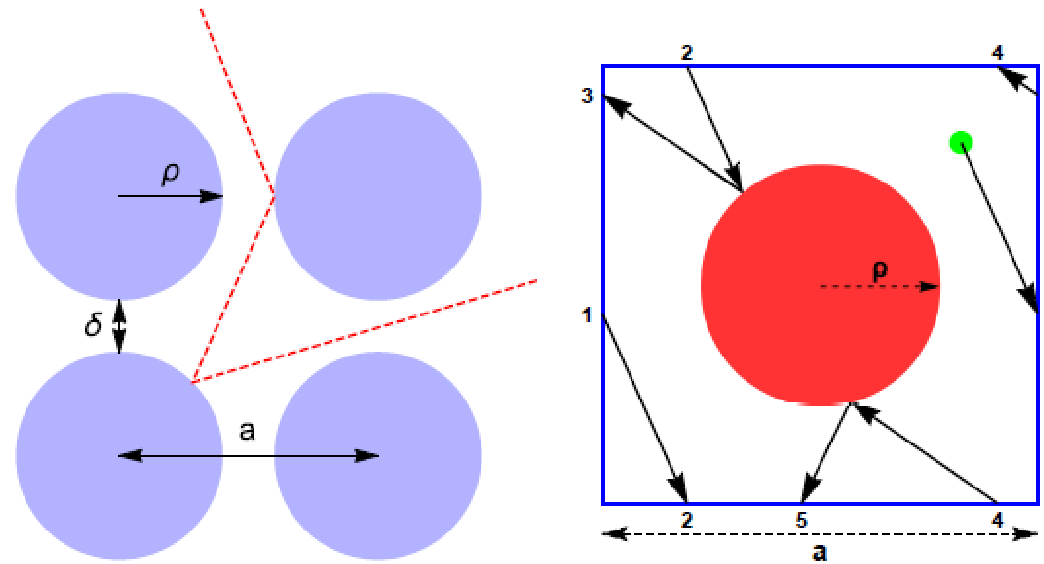




Carbon Nanotubes for WIMPs



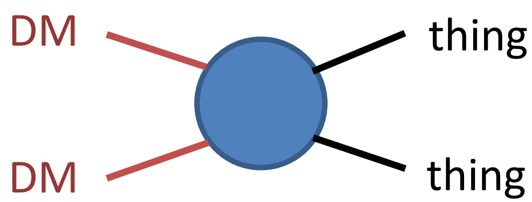
[Capparelli et al, 1412.8213]



[Cavoto et al, 1602.03216]

Theory: example #1

- **<u>Weakly coupled 2→2:</u>**



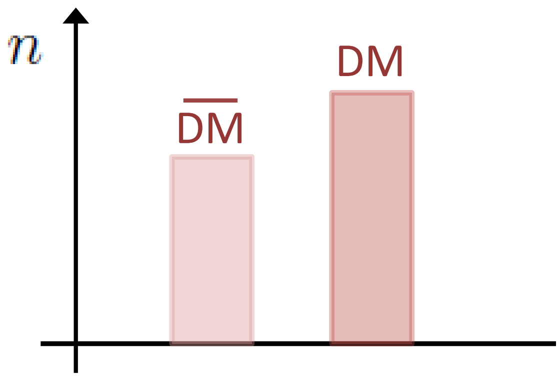
$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m_{\rm DM}^2} \qquad \alpha \ll 1$$

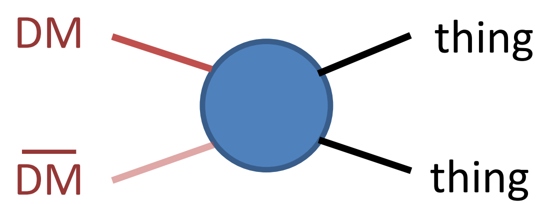
$$m_{\rm DM} \sim \alpha \times 30 \ {\rm TeV}$$

[Pospelov, Ritz, Voloshin 2007;
Feng, Kumar 2008]

Theory: example #2

- **Asymmetric dark matter:**



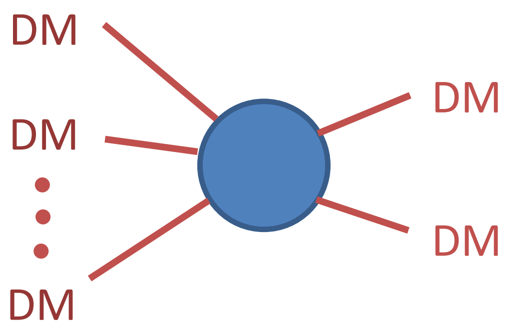


$$m_{\mathrm{DM}} \sim 5\ \mathrm{GeV} \left(\frac{n_B - n_{\overline{B}}}{n_{\mathrm{DM}} - n_{\overline{\mathrm{DM}}}} \right)$$

[Kaplan, Luty, Zurek, 2009]

Theory: example #3

- **SIMPs:** n→ 2 self-annihilations



$$m_{\rm DM} \sim \alpha \left(T_{\rm eq}^{n-1} M_{\rm Pl}\right)^{1/n}$$

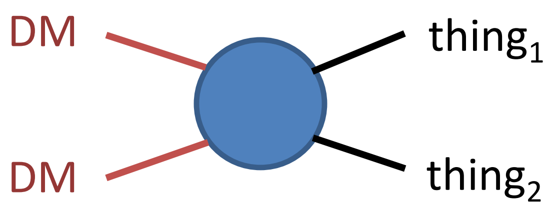
3→ 2 $\Longrightarrow$ $$m_{\rm DM} \sim \alpha_{\rm eff} \times 100 \text{ MeV}$$

[Carlson, Hall, Machacek, 1992;
YH, Kuflik, Volansky, Wacker, 2014;
YH, Kuflik, Murayama, Volansky, Wacker, 2015]

(See also elastically decoupling dark matter (ELDERs)
[Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2015])

Theory: example #4

- **Forbidden channels:**



$$2m_{\rm DM} < m_{\rm thing_1} + m_{\rm thing_2}$$

$$m_{\rm DM} \sim \alpha \times (30\ \mathrm{TeV}) \times e^{-x_F \Delta}$$

freezeout temp'

mass difference

[Griest, Seckel, 1991;
D'Agnolo, Ruderman, 2015]